DESIGN AND DEVELOPMENT OF DECISION SUPPORT SYSTEM FOR MAINTENANCE MANAGEMENT

by

S. SUDHAKAR

INDUSTRIAL AND MANAGEMENT ENGINEERING PROGRAMME

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CERTIFICATE

It is certified that this work entitled **Design and Development of Decision Support System for Maintenance Management** by S.Sudhakar has been carried out under my supervision and that this work has not been submitted elsewhere for the award of degree.

(Kripa Shankar)
Professor
Industrial & Management Engg. Programme
Indian Institute of Technology, Kanpur
Kanpur 208 016

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ABSTRACT

A decision support system (DSS) for maintenance management has been designed and developed. In developing the DSS, the concept of modelbase is used. The two major issues of maintenance viz., when to inspect and when to replace a machine or a group of machines are supported by the system. The inspection models included in the modelbase consider the objectives of minimization of the total cost and maximization of availability, while the replacement models consider the objective of minimizing the total cost over a planning horizon. For the inspection problem most of the model parameters are derived from the equipment information and history databases. For the replacement problem the relevant data are received from the user in an interactive manner. The outputs are in the form of reports that support the decision making process. The feautures include trend analysis for breakdown and sensitivity analysis of the objectives with respect to various parameters. The DBMS module and the reporting system are written in dBase III Plus language. The model execution module is written in Pascal.

CHAPTER I

INTRODUCTION

The recent trends in increasing automation, development of sophisticated and capital intensive machines and equipments and changes in management practices have resulted into severe demands on the maintenance activities. This has led to the development of a planned and controlled approach to maintenance management.

1.1 Maintenance Management : A Resume'

The growth and spread of inflation in the 1970s gave rise to a new awareness about the rising values of downtimes of the equipments and components not only in production industry but also in public services. At the same time the asset replacement costs had became so inflated that effective and intensive maintenance programs to extend the useful life of the existing assets, has became the essential aspect of the maintenance strategy. All this led the emergence of cost effective system approach to the maintenance, which was previously viewed as independent and seperate activities such as breakdown maintenance, manpower planning etc.

The physical law of increasing entropy (disorder) states that every independent system deteriorates continuously. This implies that every machine deteriorates continuously during its operation. This happens as long as external interference viz., maintenance is not applied.

Maintenance is the total of all the service functions aimed at maintaining and improving reliability performance

charecteristics of machines. It is concerned with such activities as testing and checking of working parts during their operation, inspection, the replacement and renewal of equipment and their components, etc.

The maintenance management problem deals with the determination of the optimal frequency and scheduling of inspections, optimal overhaul, replacement policies for the equipment and the components, procurement and stocking of spare parts, appropriate and suitable manpower planning and an effective information system. This problem is usually has to be solved in the presence of several constraints (such as the availability of time, costs, facilities, spare parts, manpower etc.) and technological factors (such as degree of improvement brought about by a particular maintenance action, age of the equipment and components, etc.). The two major criteria for optimal decision making, related to inspection and repair, are : the minimization of total maintenance cost, maximization of quality and reliability of operational performance. Oftenly, depending on the actual circumstances a suitable mix of the two criteria is employed. The decision making for replacement of equipment involves economic and technological constraints. In the context of present rapid developments, the technological considerations seem to be rather difficult to incorporate fully and acceptably. Morever, the economic data related to rate of return, inflation rate are difficult to predict.

1.2 Scope of The Thesis

With planned maintenance systems, maintenance planners are poorly supported with data analysis and model building expertise. The desire for information and historic data led to the ready embrace of computers and data support systems as they became available. Presently, maintenance management by computers is a popular theme, the objective being easy-to-use decision aid [24].

When computer based systems were first introduced, they represented a considerable advance over previous manual procedures and appeared as a panacea. It was felt that having a good volume of readily available information would be sufficient for management's needs. This is proving not to be so.

Information is of value if it is used. Unfortunately, when the systems were designed data for data's sake seemed to be the objective. Actual and specific uses of the data were not seriously thought thro', nor was any operation research or modelling input to ensure relation between decisions and output variables. As remarked by Christer [24], established modelling procedures will readily translate into maintenance environment. With the above in view, the main objective of the present thesis is to design and develop a decision support system with the following features:

(a) a comprehensive modelbase

(b) trend analysis

(c) sensitivity analysis

(d) reporting system

1.3 Organisation of Thesis

Chapter II reviews the salient works in the field of maintenance policies and replacement analysis of equipments and also about the computerized maintenance management.

In Chapter III, system analysis and design from the view point of developing the decision support system is presented. Chapter IV describes the modelbase, which is the most important component of the system. The implementaion features are outlined in Chapter V. Finally, in Chapter VI, conclusions and scope for further work are discussed.

CHAPTER II

REVIEW OF SOME MANAGEMENT MODELS AND RELATED ISSUES

This Chapter presents the review of some mathematical models for maintenance policies and replacement analysis. It is organised into three parts: (i) inspection models, (ii) equipment replacement models, and (iii) computerized maintenance management systems.

2.1. Inspection Models

Inspection is one of the important activity in maintenance management. Its outputs are used for planning as well as control functions of maintenance. It involves mainly study of deterioration characteristics of the components. The relevant data gathered during the study are analysed and are interpreted for various actions such as repair of deteriorated components, replacement of damaged components beyond economic repair. Quite often the equipment has to be stopped, thus making it non-productive during the inspection. This period of non-availability of equipment depends upon the type of equipment, deteriorating charecteristics of the components (e.g. failure time distribution), frequency of the inspection, inspection facility and types of actions required after inspection.

The major decision variable in inspection is to determine when to carry out the inspection. Repairs and overhauls aimed at increasing machine utlisation are undertaken based on the results of inspection. The three major objectives usually employed in the determination of optimal inspection frequencies are,

(a) minimization of cost function

(b) maximization of availabilty

(c) maximization of profit function

2.1.1 Minimization of Cost Function

Most of the work done for the generation of inspection frequencies or policies use this criteria. The total cost comprises of,

(a) inspection cost - the fixed cost per inspection,

(b) penalty cost - the cost of leaving the system in a failed state for not being able to detect the faults,

(c) state occupancy cost - the cost depending on the state of the equipment and is measured per time unit.

In the following sub-sections, inspection models are reviewed on the basis of number of states of the system.

(A) Inspection Policies for a System in One or Two States :

Many papers have appeared which look at inspection policies that can be described as being in one or two states, one of which is preferable to others. These models assume that system won't display the symptoms of failure. Only on inspection failure can be detected.

Barlow & Hunter [49] are the pioneers in this field. They proposed a model in which each inspection costs C_1 and the penalty of leaving the system in a failed state is C_2 per unit time. If X_i is the time at which i-th inspection is carried out then the total cost upto i-th inspection is given as,

$$C = iC_1 + C_2(X_i - t) \tag{1}$$

where, t is the time of failure. Let I be the random variable representing the number of inspections until a fault is detected and T be the random variable denoting the time of failure. Then, the expected total cost E(C) is given as,

$$E(C) = C_1 E(I) + C_2 E(X_I - T)$$

They showed that, for T being a continuous random variables with finite mean there exists a decision vector X_i (i = 1,2,...) that minimizes E(C).

Shahani & de Senna [43] mentioned a simple periodic policy where, $X_i = iL$, $L > 0$, $i = 1,2,3,\ldots$ and modified periodic policy where, $X_i = a+iL$; a, $L > 0$, $i = 1,2,3,\ldots$, and a and L are constants. They compared the basic model and the two periodic policies, and they point out that modified periodic policy is efficient without causing extra practical or computational difficulties.

Sometimes, the inspection processes themselves may cause deterioration of the equipment. Wattonphom & Shaw [47] have considered this phenomenon wherein inspection increases the subsequent failure rates.

Above mentioned models assumed the inspection time to be negligible.

Luss & Kander [45] proposed a set of models when duration of checking is non-negligible. They also developed model of inspection policy for several systems operating simultaneously, when service resource is limited.

(B) Inspection Policies for a System in More Than Two States

Inspection can divide a population into sub-populations according to the results of the inspection. Maintenance actions can shift an item from one sub-population to another. Sherwin [46] points out that indication of failure is often available at a small cost before important loss of performance. He proposed a model for optimizing inspection schedules when failures are self-announcing but inspection can detect signs of pending failure, so saving the cost difference between failure costs and inspection costs.

Luss [42] examines a model in which inspections reveal in addition to total malfunction, intermediate states of the system that represent varying degree of deterioration. In this Markovian model the systems degree of deterioration is described by a discrete set of states. He proposes maintenance policies, dependent on system's state at inspection times, which minimizes expected cost per unit time.

Many real life systems display symptoms of failure if they are operated in a failed state. As an example, a production process may start producing defective items after some random amount of time. If the situation is not corrected, the product quality deteriorates to a level where it is self evident to the operator that the system has failed.

Sengupta [11] considers such a system which can be in three states. It is subject to random failure at time T, with p.d.f f(t). The system is in good state in (Ø,T) and it makes transition into the fair state at time T. While in the fair

state, only at a cost of inspection failure will be revealed. If no inspection is held the system develops symptom of failure after another S random units of time. The random variables T & S are independent. This epoch (T+S) is called self-detection point. If a cost is incurred when the system is in fair state, then it is possible to reduce the total expected cost by performing suitable number of inspections over the lifetime of the system. He refers a set of planned inspection epoch as inspection schedule and proposes a differentiation technique which yields an iterative procedure for finding successive inspection epochs.

2.1.2 Group Inspection Policies

A group inspection scheduling model proposed by Subrahmanyam & Chinnarao [8] ~~have proposed a group inspection scheduling model~~, deals with a mixture of components some of which have constant failure rate while others have increasing failure rate. In this case, optimality is achieved by minimizing the total annual maintenance cost subject to constraints on system availability, number of maintenance personnel and intervals of preventive maintenance. They have shown that number of maintenance men required depends to a great extend on the cost of downtime. But, their method has mathematical limitation because of the constant failure rate assumption since constant failure rate devices donot need any PM.

S.K.Goyal et al., [40] gave a heuristics for finding inspection frequencies for a family of machines. They assume that cost of carrying out maintenance work is known and also a fixed cost which is independent of number of machines on which

maintenance work is carried out is available. Sule & Hermann [39] in a similar work, find the coordinated maintenance frequency which would save on the fixed cost associated with seperate overhauls.

Kripa Shanker and Pradeep Kumar [50] have proposed repair models for the goods producing equipment when the nature of deterioration is deterministic. They have used the results of the above models for the problem of coordinated repair of a set of equipment where the deterioration is stochastic.

2.1.3 Stochastic Decision Models with Uncertain State Information

Stochastic decision models with complete state observation have been inspected by many authors. Derman [51] has formulated the problem as Markovian decision process and showed that the optimal policy has a simple form called control limit policy.

Stochastic decision models with uncertain information have been investigated by Suzuki [7] under the assumption that the internal state of the system is known with certainity by inspection. He has developed a model where inspection does not reveal the true state of the system. He has considered the transition of the states of the system to be dependent on the age of the equipment.

2.1.4 Formulation as Control Problem

There are atleast two possible ways of representing the deterioration of a machine. The conventional way is to look at the reliability of the machine from a failure probabilistic point of view and examine it as a function of time. Another way of studying the deterioration process is to regard the quality of

the machine as a state variable and subsequently develop appropriate dynamical models to simulate the deterioration of quality as a dynamical process. Joh & Seow [21] points out that the latter approach will be more convenient from the maintenance planner point of view, since maintenance effort can be regarded as a control variable which interacts with the dynamics that governs the quality state. The resulting system can thus be formulated as an optimal control problem with the objective of determining the optimum maintenance policy while satisfying constraints on the quality of the machine as well as the budget.

Thomson [21] modelled the machine's quality state by a linear differential equation with maintenance being regarded as a control variable. The result of his study was full maintenance effort should be sustained during earlier part of the machine life span until a point at which the amount of increase in quality per unit of a maintenance do not justify the maintenance cost for optimal return and thereafter no maintenance is accorded until the machine is sold off.

C.J.Goh & K.S.Seow [21] in their paper has pointed out some limtation of the above method. The above method cannot be used when state constraints are present and also when the terminal state is required to be a prescribed state. They propose the concept of control parametrization to transform optimal control problem into a linear programming problem.[21]

2.1.5 Maximization of Availability

Reliabilty is concerned with system uptime whereas maintainability is concerned with the downtime . The parameter

which combines reliabilty and maintainability is often called availability and is of interest to many authors.

S.K.Banerjee et al.,[6] have suggested a technique to determine the sensitivity of system availability to component repair time. They define sesitivity as maintainability importance factor (MIF), which is the rate at which system availability increases as component repair time is reduced, and they give maintenance policy to maximize system availability.

2.3 Concept of Profit Maximization

Many papers have appeared in an attempt to introduce the profit concept into the area of maintenance management in order to reduce the emphasis put on the cost aspect of maintenance decisions.

The idea of profit effectiveness combines the classical sub-optimization of cost minimization and availabilty maximization into overall optimization of the profit of the firm. Handrlarski [9] describes a new parameter R, which is revenue gained per unit operation time of the machine. This combined with availability and cost function gives the profit function. He points out maximization of this function leads to optimal scheduling of PM. Because this is a single objective function, comparison of efficiency between various schemes is possible. He has shown that profit yield of age replacement is never worse than that of block replacement policy.

Steelandt & Gelders [12] presented a real life case study on the profit effectiveness of maintenance decisions in a Beligian firm. The objective of their study was to investigate whether

profit of the firm could be increased by improving the line and production efficiency. For this they constructed an integrated production-maintenance model to evaluate the output of the production line when different maintenance decisions were carried out. The result of their study shows profit maximization is a usable objective in the maintenance department, provided one is able to analyse historical records of production line and price system of the firm.

2.4 Recent Works on the Generation of Maintenance Schedule

Turco & Parolini [1] have proposed a nearly optimal inspection policy, ~~for~~ the on condition maintenance policy, which is based on systematic control of equipment. They note that failure process can be theoritically divided into two stages. The failure process (i.e.,wear) proceeds at a rate until a moment when a threshold is achieved and this is assumed as an alarm signal of closeness of failure. The model assumes different failure rate of the item before and after the threshold value and the condition of failure is univocally determined and known at the point of occurence. The model gives the near optimal inspection policy under the condition of constancy of the conditional probability between two consecutive inspections.

Tillman et al., [2] propose multiple criteria decision making process to give the optimal maintenance policy. The criteria considered by them are:

(a) Minimum replacement cost rate

(b) Maximum reliability

(c) Lower bound on mission reliability

With the use of computers, dynamic scheduling of maintenance activities has been made possible. In fixed schedule, the schedule for the entire year is determined prior to the start of the year. This method involves a load levelling process. Each piece of the equipment is analysed seperately based on the frequency of all procedures to be performed and the time required to perform the procedures. This method works until something alters the predetermined process. Thus the main problem area in fixed scheduling work is the backlogged work. In dynamic scheduling the issue of new work order is based on whether the previous work order was actually done [35].

Meisel [37] has suggested an on line maintenance verification schedule. He states that for a complex system it is often difficult to determine a schedule that is neither needlessly frequent nor dangerously infrequent and suggests a adaptive convergence method that makes the system itself to derive the maintenance schedule that yields a given MTBF.

Continuous and periodic inspection policies are used to monitor the maintenance of the production process. M.J.Rosenblatt & H.L.Lee [3] have compared the continuous and periodic inspection policies in a deteriorating production system. The cost function considered by them consists of set-up, inspection, inventory holding, defective and restoration costs. They have analysed when to switch over to periodic policies and have given the range of values of cost parameters for which continuous inspection policy is preferred.

The most interesting article that has come out recently is, the scheduling of routine maintenance using production schedules and equipment failure history [36]. This paper describes a model that was developed for scheduling of routine maintenance at an aggregate level in a manufacturing environment. The criteria used is, minimizing the expected cost of downtime of equipment.

2.2 Equipment Replacement Models

Major considerations for an effective replacement policy are,

(a) Choice of criterion : Determination of optimum equipment replacement policy involves both economic and noneconomic factors. The two commonly employed criteria are cost minimization and profit maximization and also there exist different forms within these two. But the choice depends entirely on the emphasis of the organisation.

(b) Consideration for capacity expansion or contraction: Increased demand may render a present machine, inadequate to the production level. The price/volume relationship of the product for the individual time period over the planning horizon should be known for considering this factor.

(c) Selection of production technology: The choice of production technology directly affects the utilisation of inputs. The choice for automated system or FMS directly affects the replacement of equipments.

(d) Selection of planning horizon: Analysis of replacement decisions cannot be complete without a proper selection of planning horizon. The assumption of infinite planning

horizon is questionable and also it limits its applicabilty.

(e) Capital budgeting considerations: Similar to any project selection, equipment replacement is also subject to capital rationing criteria. This restriction on funds for investments is normally imposed by management or sometimes by governments.

(e) Determination of the rate of deterioration and the rate of obsolescence: System's deterioration rate can be estimated from historical records . But obsolescence takes place completely external to the organisation and involves technology forecasting and hence, it is more difficult to determine.

Incorporating all these into a single model has not been possible. Following is the brief account of the developments of replacement models.

Theoretical works on equipment replacement decision has its origin in the articles of Taylor and Hotteling in the 1920's. Taylor developed mathematical expression for the average unit cost of a machine over a variable time period of service. He showed how the period of service could be determined such that the unit cost of production would be minimum. This period of service was termed as the economic life of the machine. From the criterion of cost minimization Hotelling generalized it to profit maximization. In 1940 Preinreich showed that the economic life of a single machine could not be determined independent of the economic life of each machine in the chain of future replacements. He assumed that all the machines in the replacement horizon are identical [25].

In 1949 Terborgh provided another milestone in the replacement field. He extended Preinreich's work to account for equipment obsolescence. His further work has come in the form of MAPI methods which are build around rate of the return analysis. This method is most popular among practitioners but they omit expansionary considerations and still adhere to like-for-like alternatives. These economic models lack the depth in characterizing the production environment against which such decisions are made.

Complexity of the replacement problem has also attracted many mathematical programming formulations. Assuming exponential functions for maintenance costs and capatilized replacement costs, Bellman & Dreyfus [23] have formulated it as the dynamic programming model. Leung [41] points out that this approach reinforces the sequential structure of replacement decisions.

Through out the seventies researchers have taken advantage of power of mathematical programming and have developed models incorporating multitude of allocation constraints.

Shore [41] argued that, Terbourgh's method will be suitable only if the organisation had unlimted supply of resources and pointed out that it is one of the many investment alternatives competing for limited resources. He posed the replacement problem as a capital budgeting problem and presented a scheme for developing cost benefit ratios so that productivity of potential replacements can be measured.

Focusing on the expansion aspect of a plant investment, Philip et.al. [41], have developed a nonlinear programming model

to determine the initial size and expansion policy for a plant investment assuming a finite horizon. Ray [41] expanded the above work and modelled the replacement problem as a network of interacting components and solved it as a mixed zero-one integer programming model with a finite planning horizon.

Following the considerations mentioned earlier, the replacement models are reviewed in the following subsections.

2.2.1 Planning horizon procedures for replacement analysis

Sethi & Chand have developed procedures for finding planning horizon for machine replacement in a technologically improving environment. In their 1979 work [17], they deal with a simple replacement model for a situation with only one technology, represented by the on-hand machine and the replacement is by a similar kind of equipment. In their 1982 work [22], they extended it to on-hand machine being replaced by any of the several technologies. Goldstein et al. [41], presented a version of the above model which emphasise on the difference between long range and short range planning.

2.2.2 Production Function Models

Smith [41] formulated the replacement problem within the framework of production theory. He expressed the cost of a production system as a fuction of the replacement interval of the production equipment. This approach enables one to investigate the effect of both input substitutions and capacity expansion.

Leung [42] discussed a case study which incorporates such factors as input substitution, expansion of output level, product price-volume relationship, deterioration and obsolescence.

The present trend in production involves growing interaction between the operations performed by each facility and also the renewal process requires large expenditures concentrated in a few times rather than small ones frequently distributed. Citing the above reasons, Umberto [26] proposes a simulation approach for multi product production line.

2.2.3 Replacement Policies for System Composed of Components

S.Yamada & S.Osaki [20] have developed optimum replacement policies for a system composed of several components. With system's life view point they classify the components into nonessential and essential units. Failure of the non-essential units does not influence the life of the system while that of an essential unit does. Assuming arbitrary failure distributions for the two class of components they analyse the age and block replacement policies and derive the optimum replacement policies which minimize the expected cost of replacement.

K.T.Mong & D.Sculli [34] have developed a replacement policy that will minimize the total cost of maintenance and the cost of purchasing new equipments. They point out that sequential replacement of components may not give the overall optimum because sometimes the cost of replacing the entire unit is cheaper than the total cost of replacing each component seperately. Assuming identical life distribution for components they have given a procedure for calculating the mean life for a group of components.

Stinson & Khumawala [16] have developed a heuristic procedure for the replacement of machines in a serially dependent

multi machine production system based on balancing of various costs like downtime costs,replacement costs,operating costs.

Murthy & Maxwell [19] discuss an optimal replacement policy with components drawn from a mixture of two types. They give conditions under which it is worth testing the system at a cost to obtain the information about the type of componenet.

2.2.4 Overhaul-Replacement Models

Effect of overhaul on operating cost and combined overhaul-replacement models have been studied by some researchers. Roll & Sachich [33] have developed a set of overhaul-replacement models under different cost structures and overhaul effectiveness. They find the number and timing of overhauls as well as corresponding replacement periods by minimizing the average cost per unit of time.

2.2.5 Other Related Works

Nakagawa & Yasui [30] have pointed out that calculation of optimum age replacement time numerically is difficult and have given a computational procedure to find the upper and lower bounds of optimum replacement time for the case of Weibull distribution.

Recent papers use optimal control theory to model the replacement problem as a control problem and use a dynamic programming approach to obtain optimal policies. Bellman [41] gave a functional equation for the replacement policies under discrete conditions. Backman [41] gave the continuous version of the same problem. Cox and Tabaga [41] outlined a model in which if the component fails close to the time of scheduled block

replacement, it is not repaired until the next planned replacement. Lake & Muhlemann [13] gave the dynamic programming approach to the problem to find the critical time at which this decision has to be taken.

D'aversa & Shapiro [4] gives a model for deciding when to optimally maintain, repair or replace the aging machines. It is essentially an accounting method for computing the present value of a cost stream in which the decision affect the cost incurred.

2.3 Computerized Maintenance Management System

For the reason such as easy manipulation of data, standardization of report, rapid information transmission and retrieval of data, computers are used for decision making in maintenance management. Maintenance management software contain some of the features like, job order system, maintenance work order system, cost accounting system, spares inventory control system, etc.

An outline of a typical computerized maintenance management software is shown in Fig.2.1 [18,29]. Current systems use the gathered data to diagnose machinery problems and pinpoint the areas in the equipment that are causing alarms. The review of more than hundred available softwares in the U.S. market appears in [48].

From the above one can find that there are plenty of maintenance management models for most of the practical situations. But, so far these donot seem to have been used by the maintenance department due to the lack of access to the models themselves and to some extend lack of computing power to

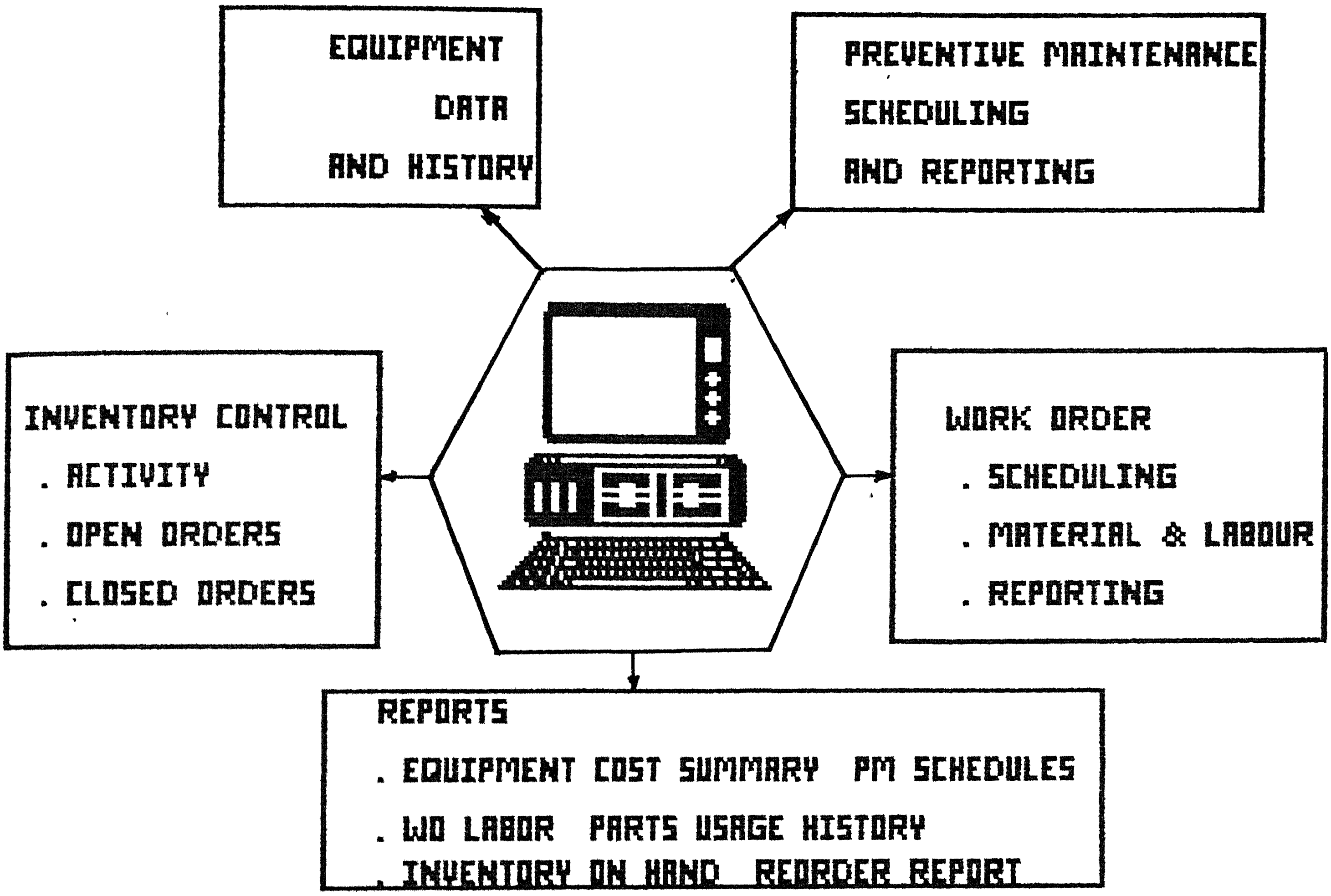


Fig. 2.1: Computerized Maintenance Management System.

calculate the various model parameters. The software so far developed seem to be preoccupied with computerizing the routine manual work.

The present thesis aims at bringing these two aspects of modelbase and computing power together by developing a Decision Support System.

CHAPTER III

SYSTEM ANALYSIS AND DESIGN

The purpose of this chapter is to design a Maintenance Management DSS and for this the concepts of DSS are outlined intially. The major steps for the design of DSS viz., modelbase, database and reporting system are outlined subsequently.

3.1 Overview of DSS

DSS is a field or an area of interest which attempts to bring together and focus number of independent disciplines to bear on decision making in the organisation. Among these are,

(a) Operation Research/Management Science

(b) Database technology

(c) Artificial intelligence

(d) Systems engineering

(e) Decision analysis

DSS is an attempt to integerate these independent disciplines, to bring their seperate technologies to bear on decision making in organizations. The most common definition of DSS is [31],

> "A DSS is a computer based information system used to support decision making activities in situations where it is not possible or not desirable to have an automated system perform the entire decision process."

In order to be successful such a system must be simple, robust, easy to control, adaptive, complete on important issues and easy to communicate with. Management Information System in

contrast deals with the structured tasks and puts relatively more emphasis on data than on models. The DSS emphasizes on decision models, the critical criterion for "knowing one when you see one" makes the psychology of DSS design and development both different from and challenging than MIS process. The typical decision aid or MIS attempts to compensate for the well known shortcomings of the intuitive scientists by building automative error checking procedures and otherwise gently prodding or forcefully pushing the user into the correct pathway. The problem is not so straight forward with DSS. A DSS is ultimately concerned with supporting decisions about planning, resource allocation or some other functional areas. Typically decision context is poorly structured or unstructured. A DSS can and should incorporate constraints derived from formal logic and work on judgement and interference.

Fig.3.1 gives pictorial framework for considering issues relevant to the design and evaluation of DSS. These issues arise at the three interfaces (shown by sets of arrows in Fig.3.1).

The first interface is between the DSS and user (DSS/U). Here, the issue is the extent to which characteristics of the DSS facilitates its usability. The second interface is between user and the larger decision making organisation of which, both DSS and user are a part (U/DMO). Here, the issue is what extend the DSS facilitates the decision making process of the organisation. The third interface is between the decision making organisation and environment (DMO/ENV). Here, the issue is whether or not DSS improves the quality of the organisation's decison making process.

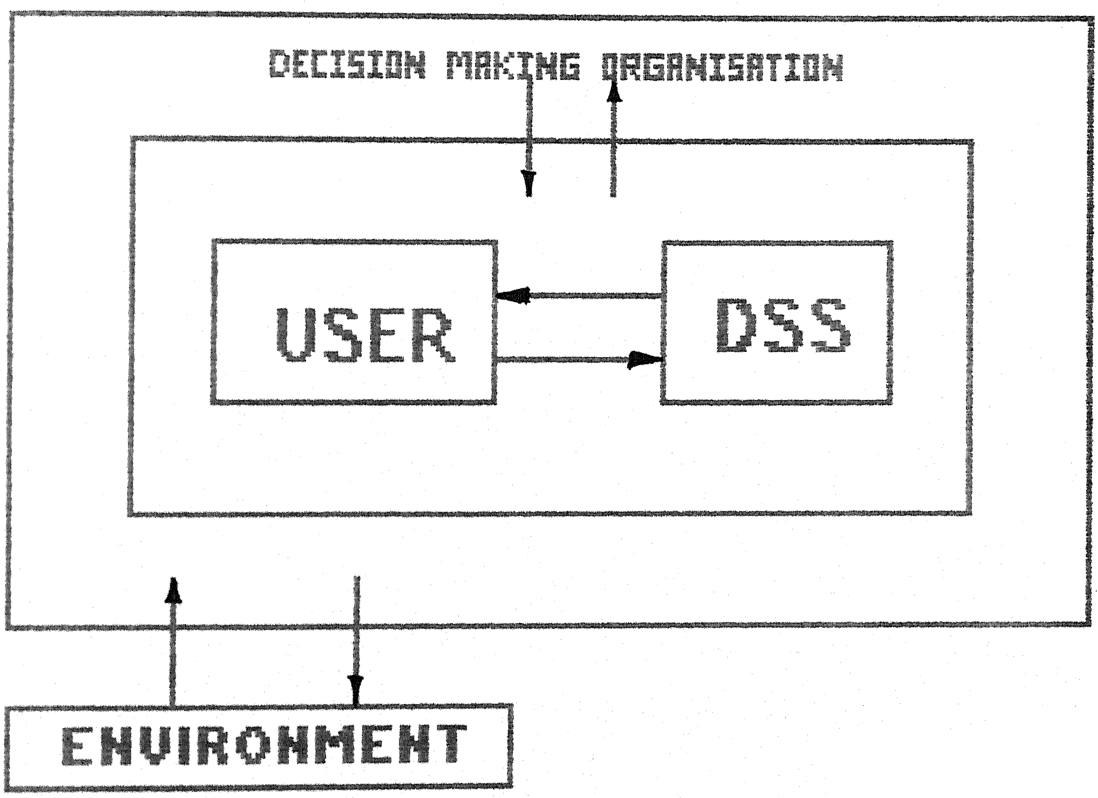


Fig. 3.1 Interfaces in DSS.

Nevertheless, the three types of interfaces do have different implications for evaluation, which justifies their use as a general framework for discussing DSS evaluation.

While DSS can be designed to aid human beings in a wide variety of tasks and situations, this range is not as great as one can imagine. It can easily be argued that there is a limited set of tasks and situations that are sufficiently robust to describe the domain of virtually any DSS.

The elements that characterize a DSS can be seperated into three major groups [31] :

(a) the underlying technological components from which DSS are built,

(b) the ways in which DSS are used, and

(c) the processes by which DSS are designed and implemented.

DSS technology has to consider both hardware and software. But, there is no specific hardware ~~necessary~~ requirement to qualify a system as DSS. DSS software can be classified into two categories namely data oriented and model oriented.

Based on the nature of decision situation they are designed to support, they can be differentiated as institutional and adhoc. Institutional DSS deals with decisions of a recurring nature, whereas ad hoc deals with situations that is neither anticipated nor recurring. Based on the criterion of flexibility and transportability across decision situations DSS is classified into specific DSS and DSS generators. A final classification is based on degree of non-procedurality of the data retrieving and

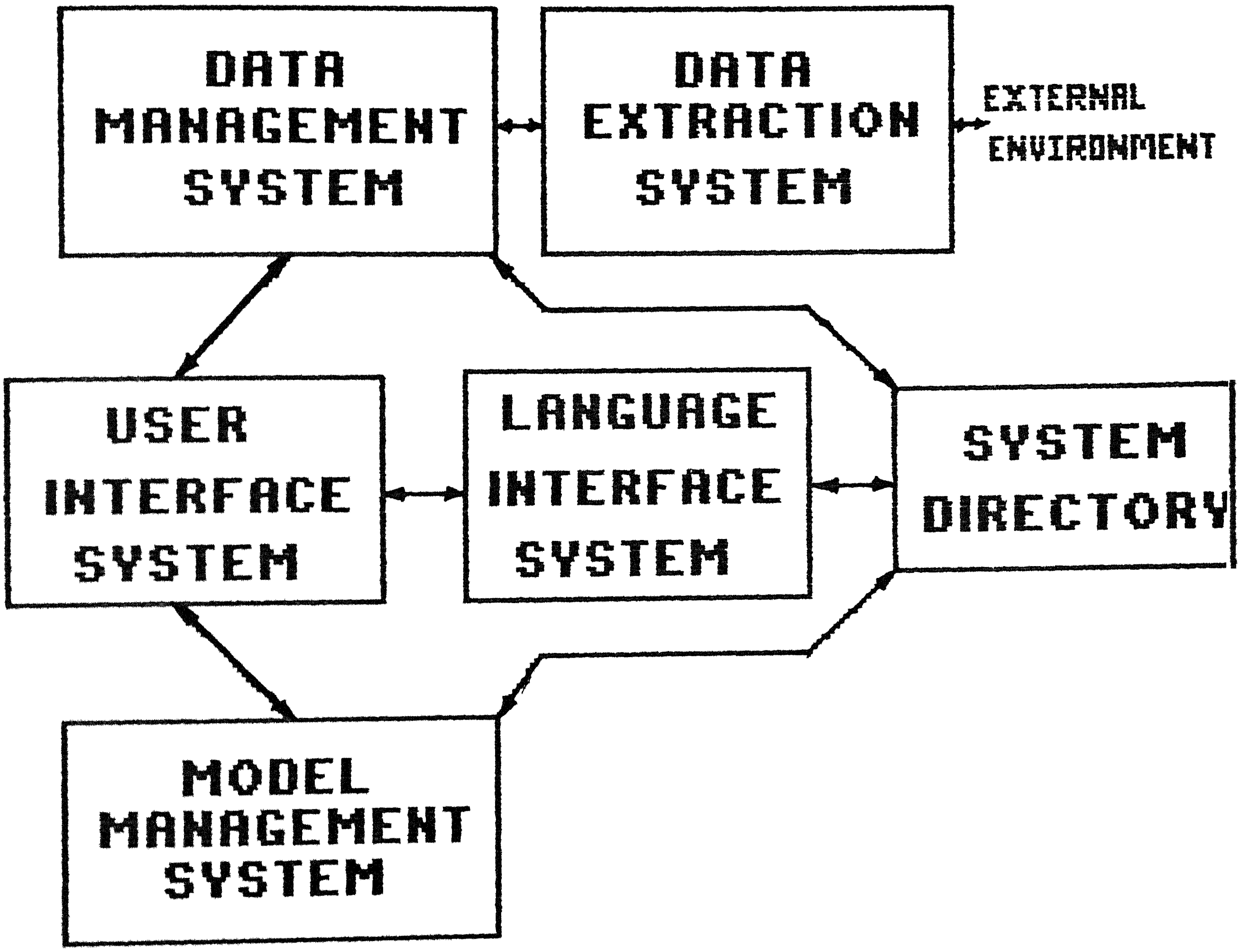


Fig. 3.2 Major Components of DSS.

modelling languages provided by DSS. Non-procedural language requires the user to specify only what is required, whereas procedural language requires step by step specification of how data is to be retrieved or a computation to be performed.

The major components of DSS software incorporating modelling capability is depicted in Fig.3.2. The software components of a DSS are quite diverse. Ginzberg & Stohr [31], points out that no DSS can contain all the components and, model management system and the potential role of artificial intelligence are unique to DSS.

3.2 Overview of DSS for Maintenance Management

From the previous discussions on the issues of maintenance management it is obvious that the DSS for this purpose should be designed to support the generation of inspection schedules and replacement analysis. With the above in view, it is proposed to design a DSS and implement it in a microcomputer, the structure of which is shown in Fig.3.3. It has basically three components:

(a) Model coordination system

(b) Data management system

(c) DSS reporting system

The model coordination system links the cost and equipment history data stored in a database to a model selection component. This component selects the model according to the available data, in a form that could be solved by the model execution module. This data transfer is taken care of by the transaction database. Report generation block does the work of selecting the data and projecting them in the proper format.

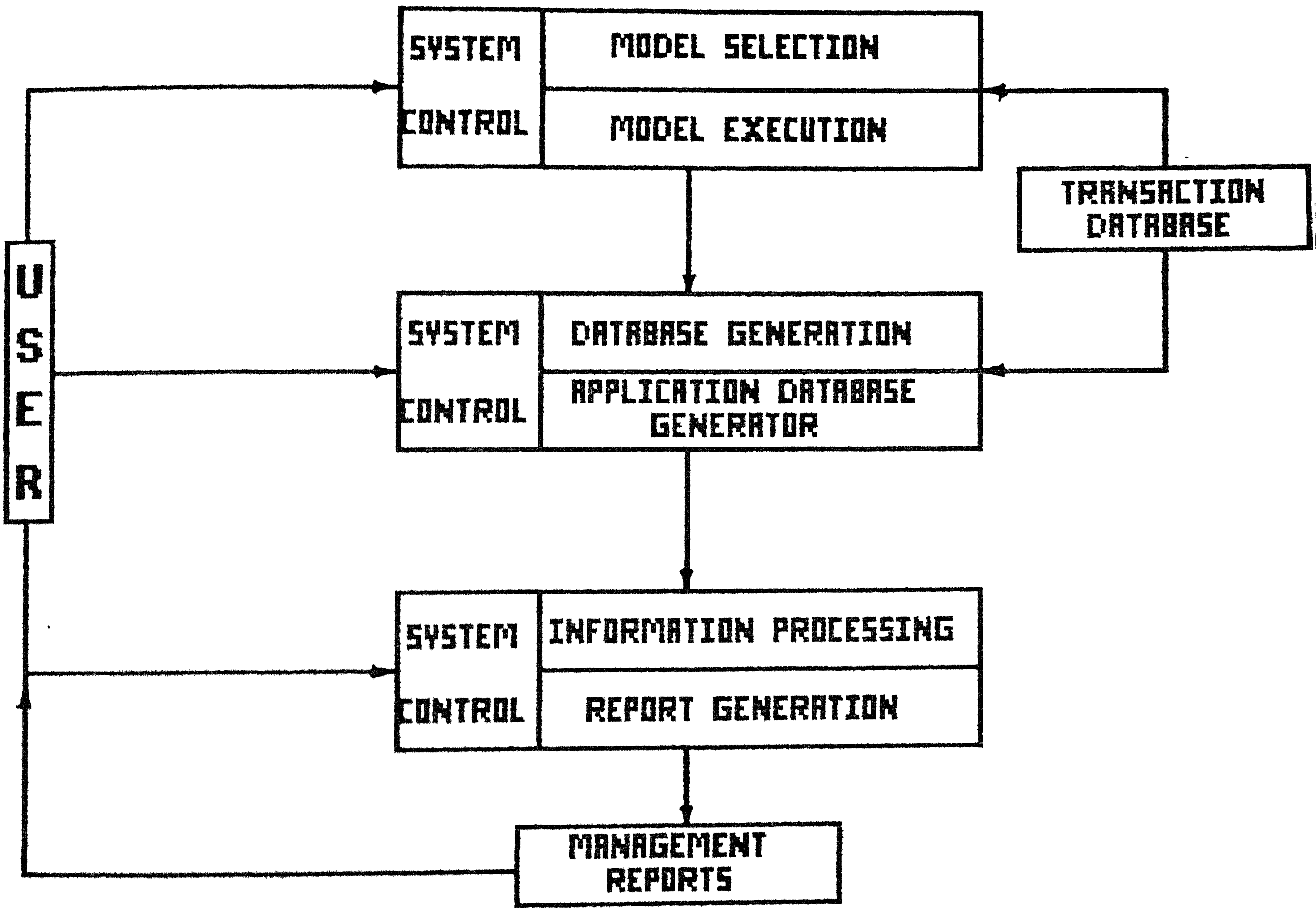


Fig. 3.3 Overview of Maintenance Management DSS.

3.2.1 Model Management

The concept of model management system, is an innovative product of DSS research. Its purpose is to facilitate both the development of models and their subsequent use during sensitivity analyses [32]. In the present implementation the idea that the user would specify the required data items and the DSS would then determine the proper sequence of operations including models to be applied and display the desired results is used. The detailed description of model base is given in the next chapter.

3.2.2 Data Management

The use of a Database Management System (DBMS) in a DSS where, the major purpose is data retrieval is direct and obvious. In model oriented DBMS other functions performed by DBMS include,

(a) management of both the inputs and outputs of the model

(b) storage and access of the model themselves

The DBMS uses the standard relational approach and all the relations are normalized. The reason for selecting relational approach is that, it is well supported in the commercial package dBase III Plus and also the fact that addition of records, deletion of records and queries can be easily accomplished in the relational form than in the network approach.

The transaction database, which is the vital link for model base, is designed based on the data requirements of the models.

3.2.3 DSS Reporting System

There is no standard approach to the design of reporting

system and its design depends on the Data Management System. Since relational approach is used for DBMS, the task of Reporting System is made easier. The data which have to be projected as reports, is accessed from the database through the use of primary keys or in some cases by search methods based on the partial data available from the user. But no provision is given to store the intermediate results.

CHAPTER IV

MODEL MANAGEMENT

As outlined in the previous Chapter, the Model Management System consists of a modelbase, model selection module and model execution module. In the following sections the salient feature of the Model Management System viz. the modelbase is described.

4.1 Model Selection

As pointed out in Chapter 1 , several established models from other areas are amenable to maintenance area. A good number of maintenance and replacement models developed to encompass various facets of practical situations derive the strength from various decision making techniques such as economic models, reliability theory, renewal theory, queuing theory etc,. For the present work, models for implementation have been selected based on the following criteria: the data requirement, performance, complexity and practical usability. The model implemented are for inspection and replacement decisions. Most of the inspection models have the objective of minimizing the total cost while some maximize the availability. The replacement models have the objective of minimizing the total cost over the planning horizon.

4.2 Modelbase

Modelbase has collections of models and it provides easy access to them. The modelbase is organised into two parts viz., inspection and replacement models.

4.2.1 Inspection Models

The modelbase has inspection models covering a variety of

situations and they are described briefly in the following sub-sections.

(a) Maximizing Availability

The first model in the modelbase deals with the preventive maintenance of a single part system called "element", for which only two states may be distinguished: the failure state and the failure-free state. The model is proposed by Gertsbakh [27]. The objeective is to find an optimal inspection time which will maximize the expected total failure-free operation time (operation readiness). The system operates in a situation which is characterized below.

The failure occurs at some random instant t. After a random latent period, the failure detection device sends a signal about failure with probability α, $0 < \alpha < 1$. The value of α is the characteristic of the failure signalling system. The system's performance essentially depends on the quality of failure detection and locating device. Nonreliable failure detection is interpreted as a probability β that the existing failure will be revealed by carrying out the inspection. ($0 < \beta < 1$)

The distribution function of the failure free operation time is assumed to be known. The efficiency of PM is measured by cost rate and this is used to express operation readiness. He forms a table of state transition probabilities and uses it to derive the operational readiness and this is explained in Appendix A.1. The physical meaning of the operation readiness is, the average rate of time in which the element is in nonfailure state. Another interpretation is, the probability that at some

arbitrary ~~taken~~ instant of time t,t->oo the element is operating without failure.

This formula for operation readiness was investigated by [27] for the following special cases,

(a) the failure signalling system gives notification of the failure with the probability $\alpha = 1$.

(b) there is no failure signalling ($\alpha = \emptyset$)

(c) the system of discovering failures during the inspection always detects the existing failure ($\beta = 1$)

In the initial phase of operation, the accumulated data won't be sufficient to assume that the failure free operation time follows a particular distribution. Gerstbakh [27] has proposed a method to calculate the operation readiness, based on the mean and variance of the life time of the element and is explained in Appendix A.2.

(b) System Composed of Components

This model due to Gerstbakh [27], which is present in the modelbase considers a system having several elements of the same type which work under the same conditions. For a group of elements there is also a possibility to carry out combined preventive repairs. The gain caused is by the fact that the group preventive repair action does not take much more time than an action carried out for an individual element. The model assumes there is a group of n elements having lifetime distribution of F(t). The failures of these elements are independent events and the failure signalling system works properly. The objective is to minimize the expected average cost per unit time over an infinite period of operation ~~period~~. The model can be described as

follows:

At the initial moment $\tau = 0$, the whole group is new and it has started to operate. Two constants (t,T) are chosen. During the period (Ø,t) only emergency repair is carried out on the individual component. If there was no failure at the instant T, the PM for the entire group is carried out. In the range (t,T) for the failed component emergency repair and for others PM is done. The problem is :

Given the various costs, the distribution function and the number of components in a machine, find the constants $t=t_o$ and $T=T_o$ which minimizes the expected average cost per unit time over an infinite operation period. The solution procedure is given in Appendix A.3. He has given computerized numerical study of the above formula for the family of Gamma distribution.

(c) The basic Cost Minimization Model

The modelbase has this basic cost minimization model proposed by Barlow & Proschan [5Ø]. This model has already been described in the Chapter 2. The detailed describtion and solution procedure is given in Appendix A.4.

(d) Tests that Degrade the Performance

The possibility that mechanical or electrical stresses might destroy the system is incorporated in the modelbase by using Wattonaphom & Shaw's model [47]. Mathematically, they allow i^{th} test to increase the failure rate without changing the form of conditional lifetime distribution. This increase is accounted by changing the effective time scale in each interval between tests. Each problem considered is completely defined by a loss function

which is similar to Barlow, Hunter's basic equation [50]. The mean loss is expressed recursively as the sum of ,

(a) a contribution incurred between the present testing time and the next one,

(b) the mean future loss after the present test.

The necessary condition for the optimal testing time t_k and the minimum mean future losses L_k are developed using the principles of dynamic programming. The detailed mathematical formulation and solution procedure are given in Appendix A.4.

(e) Self-announcing Failures

The next model in the modelbase is the Sherwin's [46] model, for finding inspection intervals for equipments, for which failures are self announcing but inspection can detect the signs of pending failure. Whether the inspection policy saves some amount depends on the base failure distribution f(t) and the cost of on condition preventive maintenance. The objective is to minimize the average cost per cycle. To express the expected number of inspections and the cycle cost a parameter, base interval risk, p is used. It refers to the conditional failure probability for an interval if inspection results are ignored. The major assumptions in this development are, items revert to orginal condition after any maintenance action, inspection assessment can be wrong only in one way i.e., assessed as surviving next interval and then fails and the base interval risk is constant for each interval t_{i-1} to t_i. Thus, the problem is to find the least costly inspection schedule. The formulation and the solution methodolgy is given in Appendix A.5.

(f) Adaptive Convergence Method

The method for constructing maintenance schedule to arrive at a user specified MTBF is also present in the modelbase. The advantage of this method, proposed by Meisel [37] are the user doesn't have to know the present MTBF and the probability distribution of failures. The method is based on adaptive convergence method and is given in Appendix A.6 .

(g) Maintenance frequency for a family of machines

The modelbase has two models for finding maintenance frequency of a group of machines satisfying two different sets of constraints. The objective is to find the inspection frequency that minimize the total annual maintenance cost.
In the manufacturing context the unit cost of the finished product may increase with time since the last maintenance. In both, the models the cost of operation per unit time is assumed to have a function of the form,

$$C(t) = a_i + b_i t^n$$

where, the exponent is same for all the machines in the family and both the coefficients are constant for the i^{th} machine. Sule & Herman [39] have found that, the above equation holds good practically, by observing cost details of machineries of a firm.

Goyal & Kusy [40] assume that there is a fixed cost which is independent of the machines being repaired, and variable cost which depends on the machine being repaired. In their model the cost function T is a continuous variable and it consists of setup cost, operating cost and maintenance cost. Their model is described in Appendix A.7.

The next model in the model base is an economic model for determining the coordinated maintenance frequencies for a group of machines proposed by Sule & Herman [39]. They have divided the maintenance schedule into two parts as minor and major maintenance programs. During major repair all machines are checked and reset. By performing this, saving in the total fixed cost of associated with the seperate overhauls on each machine is possible. Here, the total annual cost consists of production and repair cost and the production cost is expressed in terms of the equation mentioned in the previous paragraph. The procedure proposed by them determines the best value for group inspection time and the frequencies of minor repair for each machine within this time span , to minimize the total cost of repairs and production. This method is given in Appendix A.8 .

4.2 2 Replacement Models

The modelbase contains six replacement models. They are described briefly in the following subsections:

(a) The first replacement model in the modelbase is the age replacement policy of Nakagawa & Yasui [38]. In age replacement policy, a unit is replaced at failure or at age 't' whichever occurs first. The objective is to find optimum replacement time when the failure time has Weibull distribution. It is very difficult to find optimum replacement time numerically when the failure time has Weibull distribution. Their model gives upper and lower bounds of the optimum replacement time as a function of replacement costs and Weibull shape parameter. The cost data required are cost for a failed unit which is replaced and cost

for a non failed unit which is exchanged before failure. The method and solution methodology appears in Appendix B.1 . For this policy to be effective the shape parameter should be greater than 1.

(b) The second replacement model incorporated is the Sethi & Chand's planning horizon procedure model [17]. The objective is to minimize the total cost over the planning horizon. They have developed planning horizon procedure under an improving technological environment. Planning horizon procedure is useful since it is unrealistic to assume that the forecast of machine technology for the entire future is available. By planning horizon procedure they mean that there exists a time called the forecast horizon such that the first period decision based on the forecasts upto the forecast horizon is also optimal for any longer horizon problem. Thus, the solution is freed from an arbitrary horizon. At the same time, it does not require the forecast for entire future to make the optimal first period decision. They have solved the machine replacement problem using forward algorithm and have developed appropriate planning horizon results for them. The formulation and solution procedure are explained in Appendix B.2 .

(c) The third replacement model in the modelbase is the Stinsin & Khumawala's [16] multi-machine finite horizon investment renewal problem in a serially dependent production system. The problem is stated as follows. Given a finite planning horizon the decision maker wishes to decide:

(i) during which period, if any, the entire production system must be shutdown in order to make replacements,

and

(ii) what specific machine or machines in the system should be scheduled for replacement during each of these periods.

The problem involves balancing of costs. They have formulated this as an integer programming problem and have given heuristic procedure for solving this. The details of which is shown in Appendix B.3 .

(d) Terborgh's replacement model is also incorporated in the modelbase. The model can be described as folows: the existing machine is called the defender and the challenger, the latest equipment being considered. The operation cost of the defender continually rises due to deterioration, while the challenger's operation cost decreases continuously due to technological changes. The sequence of the replacement intervals is commonly referred to as replacement chain. Deterioration and obsolescence rates are assumed to be linear and the replacement intervals are identical. The objective is to identify the replacement interval that would minimize the present worth (PW) of costs over the planning horizon T. The modified approach namely Z-transform method, as proposed by Leung & Tanchoco [15] is used for finding the replacement interval. The transform method is a methodology for computing present worth of many discrete cash flow patterns. The zeta transform is direct equivalent of Laplace transform in modelling continuous cash flows. The present worth of cost (PW) based on replacing every L period has been expressed in the form,

$$PW = f(M,L)$$

where, M is a function of tax rate and depreciable life.

The detailed expression is given in Appendix B.4. When replacement occurs within the depreciable life, the value of M varies with the replacement period L. The optimal value of replacement period L, when it is within the depreciable life, is determined in a finite number of steps by enumeration. When replacement appears beyond the depreciable life, the value of M is constant. When M is constant, the above equation becomes a function of L, and a global minimum exists. The method for calculating this appears in Appendix B.4.

(e) To calculate whether it is profitable to replace existing equipment, which consists of many subcomponents, the model outlined by Mong et al. [34], is used. The objective is to find when replacing the entire unit when only one of its component fails, is cheaper than replacing components seperately in the long run. The basic assumption in the model is that the normal distribution can adequately describe the life of the component and it can also approximate the Weibull function. Another assumption is that the unit will fail to function if any one of its component ~~s~~ fails. Formulation and solution procedure is given in Appendix B.5 .

(f) Considering the replacement problem as a capital investment problem the following approach proposed by Stevens [28], is used. The objective is to find the cash flow which maximizes the minimum annual revenue requirements over the life period of the equipment. This minimum annual revenue requirement approach is commonly used to evaluate capital investment decisions.

Basically, minimum annual revenue requirements are the minimum annual gross incomes over the life of the investment that recover all expenses and provide for a stated return on the unrecovered capital. In practice minimum annual revenue requirements are generated using either normalizing or flow through method. The rate of return on the total investments will be the same for both methods of generating minimum annual revenue requirements. However, the normalizing method will give a higher rate of return on equity than the flow through method. This difference in rate of return is due to the treatment of deffered taxes in the normalizing method.

Here, the flow through method is used for finding alternate cash flows because it gives values that are closer representation of the actual cash flows since it takes into account credits and costs in the year they occur. The replacement analysis used is after-tax method and assumes a combination of debt and equity financing. The detailed steps involved in the analysis are shown in Appendix B.6.

4.3 Justification For the Use of Optimization Models

Since DSS are designed for flexible problem solving, the integeration of an optimization model within a DSS is crucial for a successful implementation.

Optimization models are used mostly for well structured problems. The optimization model provides the best vector of decisions provided that it is a perfect representation of its corresponding real world system. Therefore they should be viewed within the context of DSS because , a mathematical model only approximates the real world.

The model is often simplified because of a desire or need to reduce complexity ,information requirements or computational costs . In addition, many of the constraints in the model may be very soft in the sense that they can be modified by managerial actions if the optimal solution is not considered to be satisfactory.

Hence, the role of optimization model in managerial decision making is to support the discovery of an adaptable plan of action and valuable insight rather than to dictate what the decision should be.

Thus the selection of the above mentioned models are justified because they are flexible and are easy enough to use.

CHAPTER V

IMPLEMENTATION

5.1 System Requirements

The DSS is implemented on an IBM compatible microcomputer and it requires the following system and application software: MS-DOS operating system (version 3.1), Borland's Turbo Pascal, dBase III Plus, Lotus 1-2-3; and Hard disk.

5.2 Program Structure

The various modules of the program are shown in Fig.5.1. Detailed structure with various sub-modules and menus are shown in Fig.5.2. The user interface module is written in dBase III Plus language. Similarly, the data transfer module, DBMS module and database access modules are written in dBase III Plus language. The model execution module is written in Turbo Pascal. DSS report module is written in dBase III Plus and the graph display is done using Lotus 1-2-3.

5.3 Database Management Module

The DBMS module is vital for data analysis and serves as the data source for the Model Management System. Its pupose is to store the various data about machines, tax details, creation of transaction database, transfer of information from the model execution module to the database and to facilitate the generation of reports.

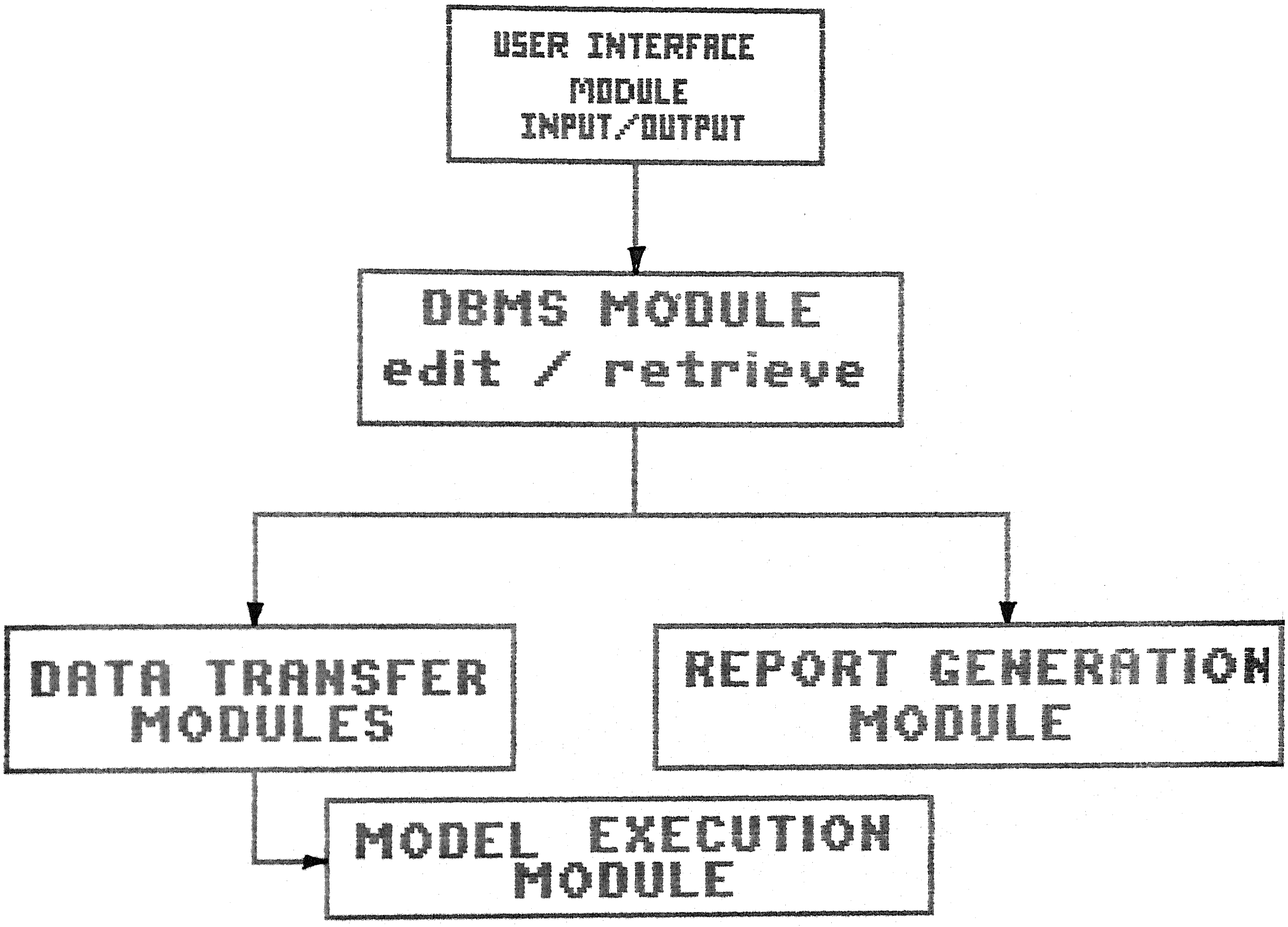


Fig. 5.1 Overall program structure.

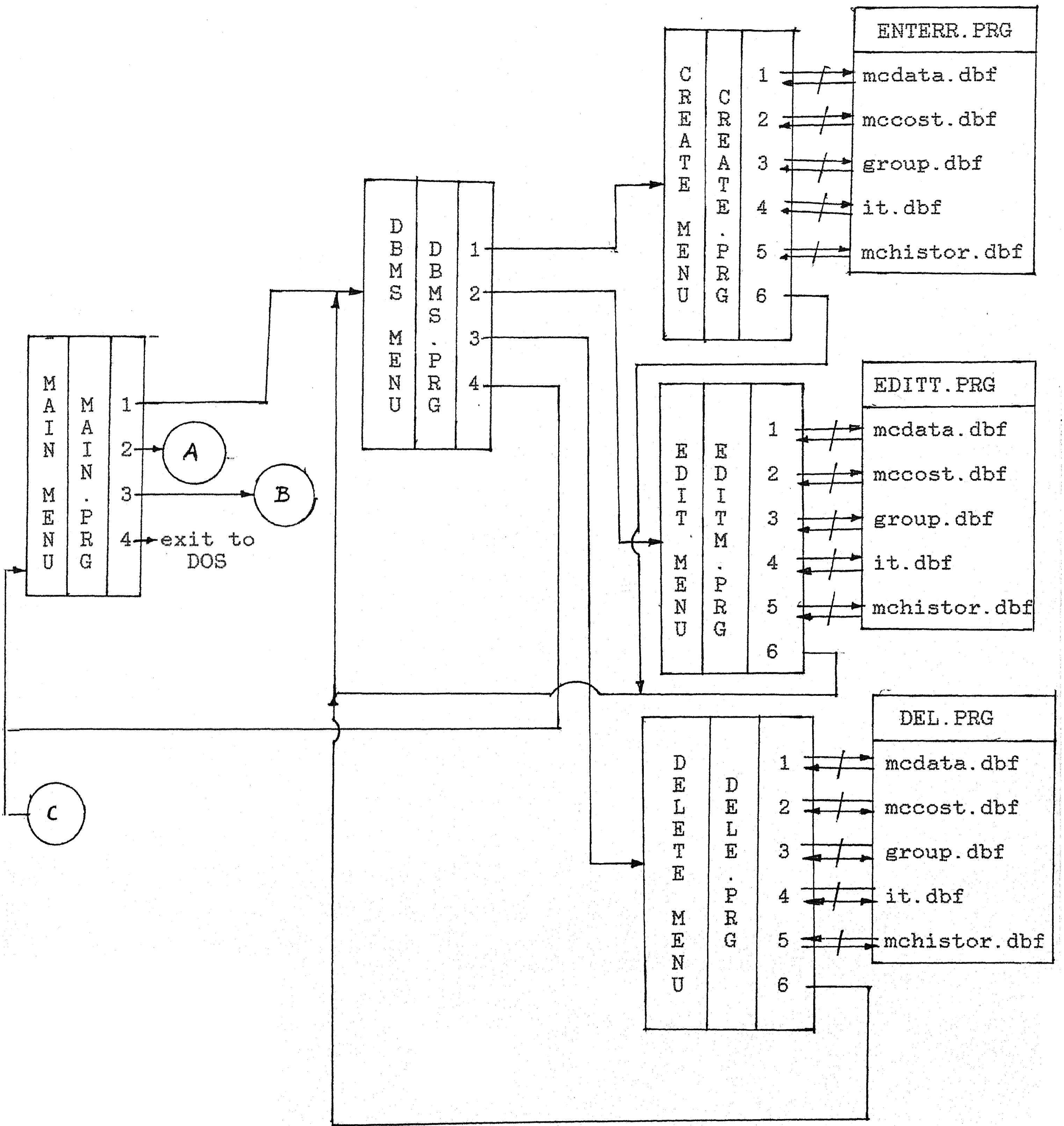
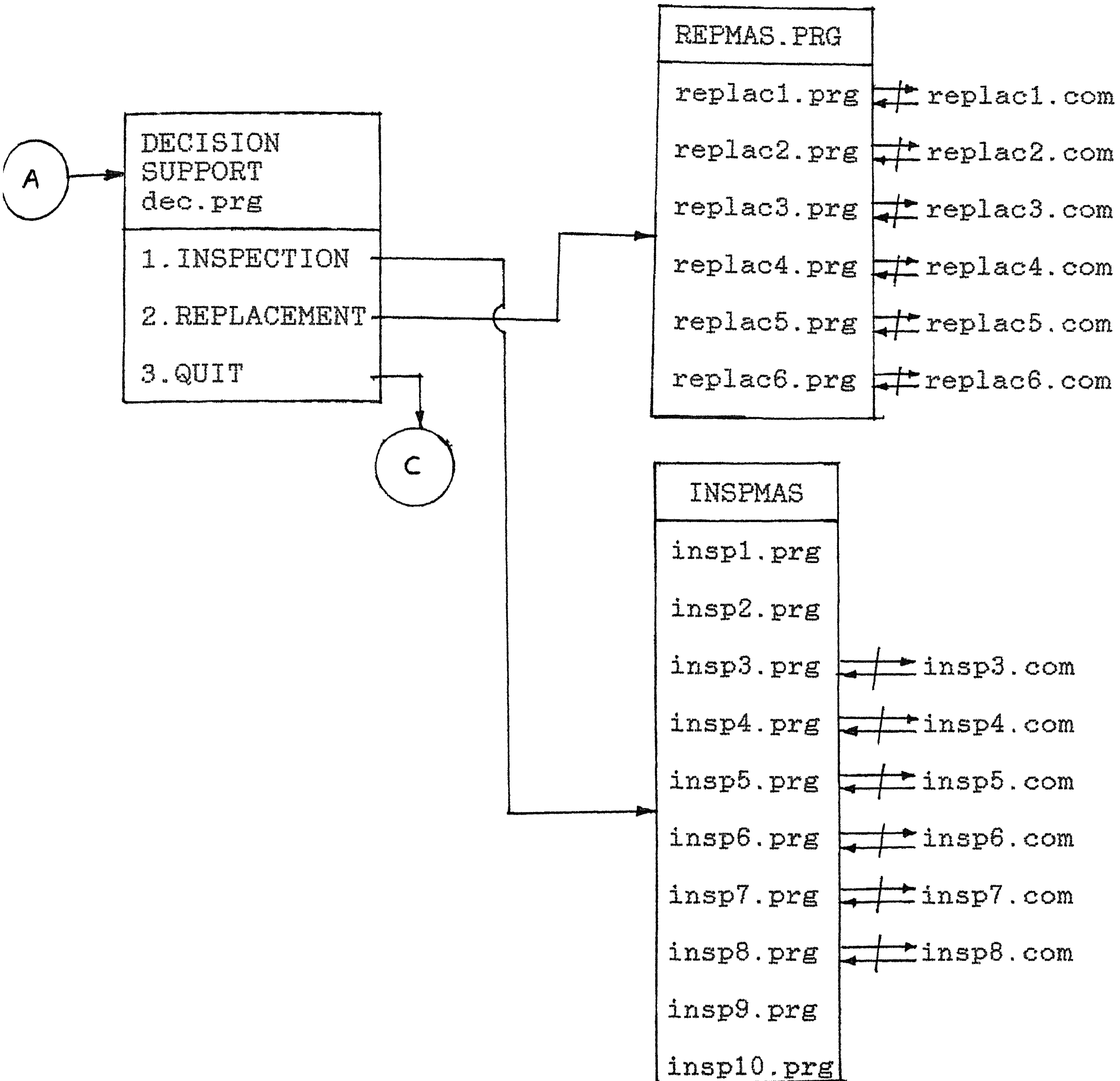


Fig. 5.2 : Detailed Programme Structure



/ - denotes the use of transaction database and model or distribution parameter routines.

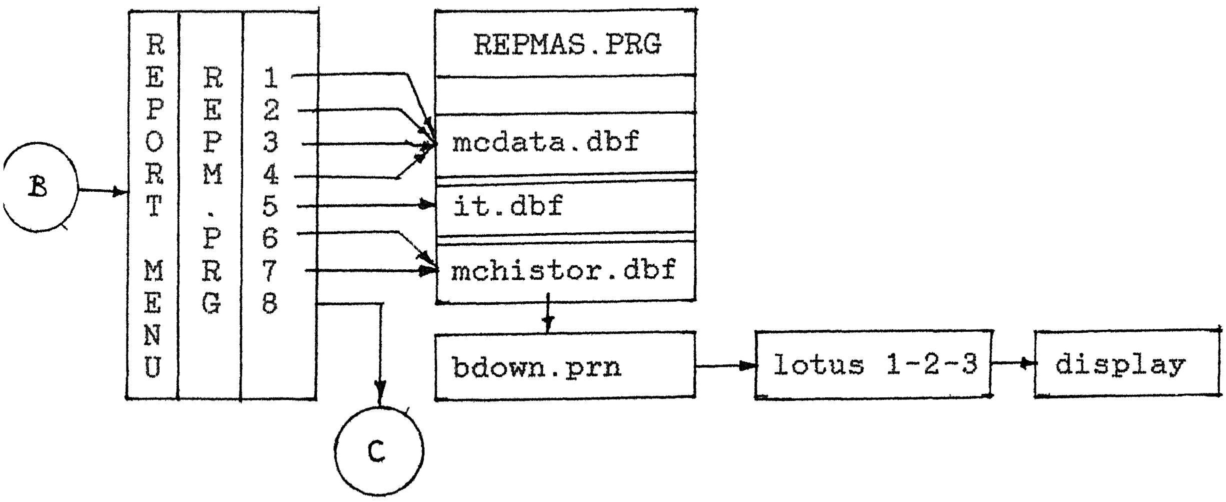


Fig. 5.2(contd) : Detailed Programme Structure

5.3.1 Database

The purpose of the database is to store the data and to facilitate easy access to a specific data. Here, the two major database created are machine information database and machine history database. Structure of the database are shown in Appendix C. The machine information database is indexed on the field 'systemno' which is unique for every machine i.e., for every record. For the machine history database the combination of all the fields should be the key to uniquely determine a record. But, on the assumption that for a machine there won't be more than one inspection report in a day, the combination of 'date' and 'systemno' fields is used as a key. The structure of the transaction database depends on the model data requirements. Hence, to minimize the number of transaction databases, similar models (from the input data point of view) are grouped and for them a common database is used. Note that, the transaction database is not for permanent storage of data and its use is only as a link between modelbase and database.

5.3.2 Create/Edit/Update/Retrieval

This module of the program has the ability to store and retrieve descriptive information and enter for each individual equipment the cost data, installation date etc. The user can add new equipment records and print existing equipment record information. For each machine the user has to specify a unique identity which can be based on factors like the department to which it belongs, the function of the machine. While entering a new record, after filling all the fields if the user wants to

edit them there is a provision for current edit. The user has the the facility to access an existing equipment record by specifying its unique number. If he doesn't know, he can print the equipment list containing the code and other details department-wise or the whole plant. As mentioned in the previous Chapter, the income tax details are vital for replacement decisions. Income tax details are permanently stored in a databbase .Hence there is a provision for entering or editing them. Similarly, the user can enter details about group of machines and the details about major subsystems of a machine.

The user has the option to search for and display or print all equipment records which satisfy various user specified criteria including department, manufacturer, function.

5.3.3 Setting Job Priorities

The user should always assign a priority rating to every job request. Before a work order is authorized and planned the priority rating may be reassessed and possibly changed according to set priority guidelines. Priority is generally established by using either a multiplier system or a straight numeric system. In the present implementation a straight numeric system of 1 to 5 is used. Priority definition for this system is as follows:

condition	priority code
When an extremely unsafe condition exists that may endanger life critical production equipment is down. In such cases, overtime will be assigned if necessary to handle the repair work.	1

Urgent work that should be started as soon as possible i.e., within 24 hours.	2
Essential work for which immediate completion is not critical but work should be started within the next week.	3
Work to be scheduled when parts, materials equipment and personnel are available.	4
Work requiring extensive planning and scheduling that may be designated for a shutdown period.	5

5.4 Model Management Module

The model execution module is written in Pascal. Most of the models require calculation of Weibull distribution parameters. Here the method of simple linear estimator as proposed by Kingston & Patel [44], is used. The difficulty faced in linking transaction database and modelbase was that they can be connected only through a text file.

.4.1 Sensitivity Analysis

Sensitivity analysis is provided for important parameters of the models. For the replacement models, tax rate is chosen as the parameter for sensitivity analysis and for Terborgh's replacement model the deterioration and obsolescence cost rates are considered. For the age replacement model [38], the ratio of cost is chosen as the parameter. For the inspection models, the probability of failure signalling system, MTBF, inspection cost and penalty cost are chosen as parameters for sensitivity

analysis.

5.4.2 Decision Support

This module of the program gives the user the option of requesting aid for either inspection or replacement decisions. Some models require the user to give appropriate data. Finally, it shows the options in the form of a table, which lists the conditions and the corresponding feasible values of the decision variable. The user by using this table as a guideline can give the values for the decision variable and it will be stored permanently in the database.

5.5 User - Interface Design

5.5.1 Screen Displays and Menus

The menu interface design lets the user select from a menu of alternatives such as report names or computational commands. Since the DSS requires larger number of functions it requires many menu items and hence they are structured. The menus are arranged in a hierarchical structure with the main menu providing access to major program fuctions and other menus under each main menu selection gives necessary access to specific functions and feautures. Menus are used to present several alternate choices and are not just used to present simple questions. The different levels of menu and options provided in them are shown in Appendix D.

5.5.2 Entry Format and Keyboard Usage

Screen entry format are similar throughout the program. The number of keystrokes required to perform program functions are

minimized to the extent possible. Erroneous keyboard entries or keystrokes which are not permitted at a specific location within the program, cause a display of error message and results in no action.

The design of input/output format is done in such a way to maintain the correspondence between the input /output forms or thought patterns familiar to the user. The DSS presents an ouput within which the user may fill input that will either modify the current output or result in a different output.

5.6 Report Generation and Trend Analysis

There are many reports that can be generated for use in controlling maintenance but here the number of reports is limited to those which are most benefitial and will be used. The reporting system contains provision for displaying the final results either on the screen or on a printer. The program generates the following reports: equipment cost summary, equipment location, equipment history, group equipment report, replacement schedule and inspection schedule. Appendix E gives the sample output of each report.

The equipment history report gives the details of the past history (from the user specifed date) till the current date. The replacement schedule report gives the list of equipments to be replaced in a particular year. The inspection schedule report, gives the list of equipments to be inspected during a particular user specified week with its location, priority rating, department.

For a particular machine one can view how often the machine

has failed recently. This helps the maintenance planner in deciding whether to replace the particular machine or to take corrective actions.

CHAPTER VI

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

6.1 Conclusions

A DSS for maintenance management has been designed and implemented to support the maintenance planner in taking decisions about when to inspect and when to replace a machine or group of machines. The concept of modelbase has been used in the system. The advantage of this DSS is that, it can use the same data which is available with the existing manual or computerized maintenance management system. Most of the data for supporting the inspection decision is retrieved from the machine information and machine history database files. Other details like what MTBF user wants, state of the failure signalling system are got through the keyboard. The data requirement for the replacement analysis is large and is got from the user in an interactive fashion. Hence, the decision maker can use the system easily and also the system is user friendly. The system gives the facility for identifying the trouble prone machine. The outputs mainly, inspection and replacement schedules are in the form of practically usable reports. As mentioned earlier, the modelbase covers most of the situations where user is in need of decision support.

The system is very slow and the modelbase can be strenghtened. Due to the limited computing power of PC and lack of access to mathematical/statistical packages, many slowly converging models were not incorporated in the modelbase.

6.2 Suggestions

This can be implemented in a minicomputer or in a network environment where one has access to a faster DBMS and powerful packages. The modelbase can be strengthened and spare parts control can be incorporated. By incorporating craft & manpower database, maintenance time standard databases the existing DSS can be extended to support and evaluate maintenance budgetary decisions.

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APPENDIX-A

A.1 Gertsbakh's Models : [27]

The inspection problem has been formulated as a Semi Markovian Process. The system can be described by the following states : (a) the element is operating E1, (b) the element is inspected, there is no failure E2, (c) the element is inspected, at the beginning of the inspection there was a nondiscovered failure E3, (d) the element is repaired E4, and (e) the element is functioning in the presence of a nondiscovered failure E5. The efficiency of PM is measured by rate of return per unit time and this is used to express operation readiness. In the case of an operation for an infinite time interval, only Markovian stationary strategies are considered. This result is used in making the inspection interval constant.

Calulation of probabilities of transition form Ei to Ej:

At the instant t, the element is in state E1 and inspection interval T is selected. The transition E1 -> E2 will occur iff there is no failure during the interval (t, t + T), (with the probability 1-F(T)). The transition E2 -> E3 occurs if at some instant $t + \tau$, $0 < \tau < T$, the failure occurs but no signal about it is recieved. The corresponding probability is,

$P\{E1 \rightarrow E2\} = F(T)(1-\alpha)$

Similarly, $P\{E1 \rightarrow E4\} = \alpha F(T)$ and $P\{E2 \rightarrow E1\} = 1$. Refer Fig. A.1.

The only possibility of going from state E5 is to E3. The $P\{E3 \rightarrow E4\} = \beta$. The matrix of transition probabilities has the

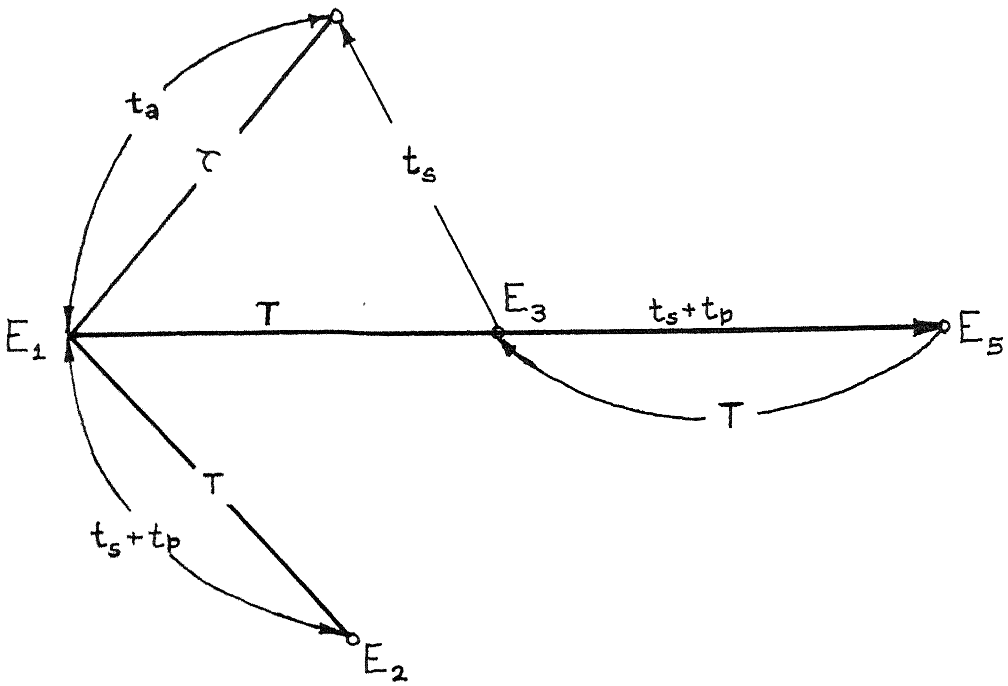


Fig. A.1: Transition diagram for the case of nonreliable failure signalling $(0 < \alpha < 1)$ and $(0 < \beta < 1)$.

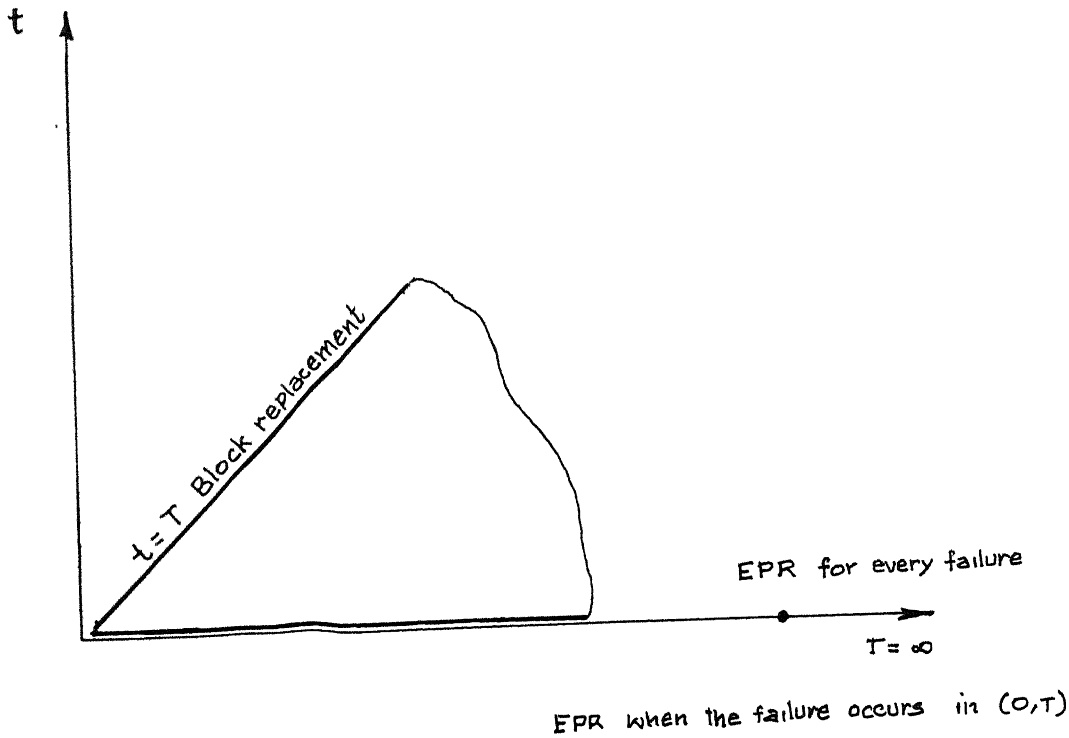


Fig. A.2: Phase plane (T, t).

the formula becomes,

$$g(T) = \beta \int_0^T (1-F(u))du \, [\beta \int_0^T (1-\alpha F(u))du + (1-F(T))\beta(t_s+t_p)$$

$$+ F(T)((1-\alpha)(1-\beta)(t_p + T) + \beta t_a + (1-\alpha)t_s]^{-1} \quad (1)$$

Assuming that the failure free operation follows Gamma distribution, the following cases are analysed,

Case 1. $\alpha = 1$

Case 2. $\beta = 1$ and $0 < \alpha < 1$.

A.2 Optimal Inspection Policy using Only Data on Mathematical Expectation and Variance:

The formula for operation readiness (1) is modified to ,

$$g(T) = [\, 1 + \frac{1-(1-b)(1-F(T))}{\int_0^T (1-F(x))\,dx} \, t_a \,]^{-1}$$

where, $b = t_p/t_a$.

The optimal inspection time is determined by minimizing this equation [27,pg. 87].

A.3 Group Preventive Schedule when the System is Composed of Components working under the same condition

The model can be described as follows:

At the initial moment $\tau = 0$, the whole group is new and it has started to operate. Two constants (t,T), $t < T$ are chosen. During the period $(\emptyset,t)$ only emergency repair is carried out on the individual component. If there was no failure at the instant T, the PM for the entire group is carried out. In the range (t,T), for the failed component emergency repair and for others PM is done. The problem is :

Given the various costs, the distribution function and the number of components in a machine, find the constants $t=t_0$ and $T=T_0$ which minimizes the expected average cost per unit time over an infinite operation period. Refer Fig.A.2.

Let t_{er}, t_{epr} and t_{pr} denotes the downtimes for carrying out the emergency repair, emergency preventive repair and preventive repair. Then,

$t_{er} = b_1 + b_2 = b,$

$t_{pr} = nb\alpha,$

$t_{epr} = b_1 + nb\alpha$

where,

b_1 is the time spent for locating failure,

b_2 is the time spent for replacement of one element

α is the coefficient which reflects the reduction of downtime

Formula for expected cost per unit time:

$$u(t,T) = nb \frac{M(t) + \alpha + b_1 b^{-1} n^{-1} \Psi_{at} (T-t)}{t + \int_0^{t+T-1} (1 - \Psi_{nt}(x))\, dx}$$

where, $\Psi_{nt}(x) \rightarrow$ DF of the RV which represents the distance from the renewal point.

A.4 Barlow, Hunter's Basic Inspection Model [50]

If x_i, $i = 1,2,\ldots,$ is the time at which i^{th} inspection is carried out then the total cost upto i^{th} inspection is,

$C = iC_1 + C_2 (x_i - t)$

where t is the time until failure, C_1 is the cost of inspection and C_2 is the cost of leaving the machine in a failed state. The number of inspections until a fault is a random variable I. Then,

number of inspections until a fault is a random variable I. Then, the expected total cost is,

$$E(C) = C_1 E(I) + C_2 E(x_I - T)$$

If the time until failure, T, is continuous variate with finite mean, then a vector called x_o, which minimizes E(C) exists. To find the optimum inspection schedule differentiating the above equation the recurrence relation is got.

$$x_{i+1} - x_i = \frac{F(x_i) - F(x_{i-1})}{f(x_i)} - C_1/C_2 \qquad (1)$$

where, f(.) is the p.d.f. and F(.) is the c.d.f. of T. The inspection times can be calculated once x_i is known. If the density of the random variable T is such that f(x-a)/f(x) is nondecreasing in x for {x / f(x) > 0} and a>0, then checking intervals form a non-increasing sequence. For the class of distributions, that includes members of the Gamma, Weibull the following iterative method is used to obtain the optimum schedule:

(i) Start with a value of x_1

(ii) Compute x_2, x_3, ...

(iii) If for some i, $(x_{i+1} - x_i) > (x_i - x_{i-1})$ decrease the current value of x_1. Recompute x_2, x_3,..

(iv) If for some i, $(x_{i+1} - x_i) < 0$, increase the current value of x_1. Recompute x_2, x_3,...

If $k = C_1/C_2$, then recurrence relation (1) provides a one parameter family of inspection vectors that minimizes E(C).

A.4 Wattonaphom's Model :[47]

This model aims at finding the inspection schedule when the inspection itself causes the deterioration of the equipment. The

problem considered is completely defined by a loss function,

$$L' = E(C_1 N + C_2 D + C_3 t)$$

where C_1 is the checking cost

C_2 is the cost of leaving the system in a failed state

C_3 is the cost benefit if failure is identified during inspection.

The mean loss is expressed recursively as the sum of ,

(a) a contribution incurred between the present testing time t_k and the next one t_{k+1},

(b) the mean future loss after the present test at t_{k+1},

$$L_k = E(loss/t_k < t < t_{k+1})\, P(t_k < t < t_{k+1}/t_k < 1) + E(loss/t_{k+1} < 1) P(t_{k+1} < t/t_k < t)$$

The necessary condition for the optimal testing time t_k and the minimum mean future losses L_k developed using the principles of dynamic programming for exponential life time distribution are,

$$L_k^o = C_1 - C_3/ \lambda_k + C_2 \delta_k^o$$

$$\delta_k^o = (1/\lambda_k) \ln [(\lambda_k/C_2)\, L_{k+1}^o + 1 + C_3/C_2]$$

where δ_k is the inter-checking time.

By knowing the maximum number of inspections the end condition can be derived .

The algorithm for computation of testing intervals in relation to a failure rate sequence $\lambda_0 < \lambda_1 < \lambda_2 \cdots$

1. Choose an initial maximum number of tests, M_1 .
2. Assume $L_M^o(M_1) = C_1$ and use the above mentioned recursive relation to find $L_o^o(M_1)$.
3. Repeat for $M_2 > M_1$, ETC.

4. Stop when $\delta_i^O(M_{k+1})$ and $\delta_i^O(M_k)$ are sufficiently close.

A.5 Inspection Intervals for Equipments for which Failures are Self-announcing: [46]

The problem is to find the least costly inspection schedule and compare its long term cost rate with periodic policy i.e. to minimize the average cost per cycle.

Base interval risk p is used to express expected cycle time and cost rate and is defined as the conditional failure probability for an interval if inspection results are ignored. The Sherwin [46] model is described mathematically as:

the survival function , $R(t_i)=(1-p)^i$

the expected number of cycle cost, $E[C] = E[I]C_I+(1-r)C_M+rC_F$

where r is the ratio of actual to base interval risk

n is the maximun number of inspections

C, C_I, C_M, C_F are cycle cost, cost ofinspection, on-condition maintenance cost and downtime cost

E[I] is the expected number of inspections.

If the costs are fixed the above equations can be expressed in terms of p and the optimum schedule will be obtained at p=p* when

$\min_p[E[C]/E[T]]$

where E[T] is the expected cycle time and it consists of expected number of failures and PM maintenace each multiplied by its probability of occurance in a cycle.

A.6 Adaptive Convergent Method: [37]

The adaptive convergence method as proposed by Meisel [37]

is as follows,

(a) choose a initial schedule of maintenance to inspect the equipment every t_1 units of time

(b) after the i^{th} failure at a time t_i since the last failure a new schedule of maintenance is initiated, where,

$$T_i = T_{i-1} + a_{i-1}(t_{i-1} - \mu_0)$$

where μ_0 is the desired MTBF and a_i belongs to a sequence of scalars.

A.7 Goyal's Method for Maintenance frequency for a Family of Machines:[40]

The objective is to determine the maintenance frequency of each machine which minimizes the sum of the relevant costs per unit of time. Their model is described below. The total cost per unit time, Z(T), consists of the following :

1. cost of maintenance set-ups = M/T
2. cost of carrying out maintenance :

the repair work on the i^{th} machine is carried out at the time interval of TK_i. Therfore the total cost of the repair work done on all the machines equals,

$$(M_i/K_i)/T$$

3. operating costs of the machines :

As the repair work on the i^{th} machine is carried out at time intervals of TK_i, the total operating time per unit of time is given by,

$$a_i + [b_i(TK_i)^n/(n+1)]$$

where,

n = exponent of the cost function,

n = exponent of the cost function,

M = fixed cost associated with set-ups required for maintenance work,

T = time interval between successive maintenance work,

$Z(T)$ = total cost per unit time,

a_i, b_i = constants in the cost function, and

K_i = the ratio between frequency of maintenance cycle and the frequency of maintenance on the machine.

In the total cost function T is a continuous variable and K_i's are discrete variables.

Approach for determining economic policy :

At a given set of K_i values, the economic value of T can be obtained by setting $dZ(T)/dT = 0$ and solving for T and the result is $T(K_i)$. Substituting this back in the total cost function results in another equation which is convex for fixed values of K_i and this can be easily solved.

A. Sule & Harmon's Group Maintenance Polcy: [39]

The cost of operation per unit time is assumed to have a function of the form,

$$C(t) = a_i + b_i t^n$$

where, the exponent is same for all the machines in the family and both the coefficients are constant for the i^{th} machine and note that Goyal et. al.[40], have also assumed the same expression for the production cost.

The total cost of operation consists of the cost of repairs plus the cost of production. They assume that between two successive repairs the unit cost of production follows the above equation. The average cost on minor repair on machine i

is S_i. After an interval of cycle time T, a major repair is performed at a cost of S. The cost of major repair is less than the total cost of minor repairs performed on all the machines.

total cost/year = cycle cost * number of cycles/year

where, cycle cost is the sum of the following:

$$\text{the repair cost /cycle} = S + \sum_{i=1}^{N} (k_i - 1)S_i$$

where $k_i - 1$ is the number of minor repairs performed on machine i in a cycle.

$$\text{The production cost per cycle} = \sum_{i=1}^{N} k_i \int_0^{T/k_i} (a_i + b_i t^n)dt$$

The total cost /year ,TC,

$$TC = \frac{1}{T}\left[S + \sum_{i=1}^{N} (k_i - 1)\, S_i + \sum_{i=1}^{N} k_i \int_0^{T/k_i} (a_i + b_i t^n)\, dt\right]$$

Setting dTC/dT = Ø and solving for T,

$$T = \left[\left(\frac{n+1}{n}\right) \frac{S - \sum_{i=1}^{N} S_i + \sum_{i=1}^{N} k_i S_i}{\sum_{i=1}^{N} b_i/k_i^n}\right]^{1/(n+1)} \qquad (3)$$

Substituting this in TC,

$$TC = f(G), \quad \text{where} \quad G = \left(S - \sum_{i=1}^{N} S_i + \sum_{i=1}^{N} k_i S_i\right)^n \left(\sum_{i=1}^{N} b_i/k_i^n\right) \qquad (4)$$

The minimzation of TC w.r.t k_i is equivalent of minimization of G,

$$G = G = \left(S - \sum_{i=1}^{N} S_i + \sum_{i=1}^{N} k_i S_i\right)^n \left(\sum_{i=1}^{N} b_i/k_i^n\right)$$

Solving for k_j,

$$k_j = \left[\frac{S - \sum_{i=1}^{N} S_i + MS_1) M^n}{b_1} \cdot \frac{b_j}{S_j} \right]^{1/(n+1)} \qquad (5)$$

The procedure proposed by them determines the best values of T and the frequencies of minor repair for each machine within this time span , to minimize the total cost of repairs and production. This method is,

Solution Procedure:

The following iterative method is proposed by Sule & Harmon [39]

1. Determine the ratio's, b_j/S_j for $j = 1, \ldots N$. Rearrage the machine numbers, if necessary, so that machine 1 is one with the smallest ratio.
2. Set $M = 1$.
3. Set $k_1 = M$.
4. Calculate k_j's from (5), rounding off to the nearest integer values greater than zero.
5. Calculate the total costs from (4).
6. If it is the first iteration goto step 8. Otherwise, go to step 7.
7. If the cost obtained from this iteration is greater than the cost of the previous iteration goto step 9. Otherwise, goto step 8.
8. Increase M by 1 and goto step 3.
9. Calculate T from (3).
10. The solution associated with the least cost alternative the one selected.

APPENDIX - B

B.1 Age Replacement Policy [38]

The expected cost for the age replacement policy with planned replacement time u_o is [49, Chap.1],

$$C(u_o) = [c_1 \text{ weif}(u_o;\beta) + c_2 \text{ weifc}(u_o;\beta)]/M(u_o)$$

and the optimum replacement time is the unique solution of the above equation and can be obtained by the usual calculus method. where,

u_o is the replacement time for operating unit,

c_1 is the cost for a failed unit which is replaced,

c_2 is the cost for a mon-failed which is exchanged before failure, $c_2 < c_1$,

α,β are the shape and scale parameters of Weibull distribution,

weif$(.;\beta)$, weifc$(.;\beta)$ are the Cdf and Sf of a std. Weibull distribution,

$M(u)$ is the mean life during interval $(o,u]$.

The calculation of unique value for u_o is difficult and the range derived by Nakagawa & Yasuki [38] is,

$u_1 = \varepsilon^{1/\beta}$ which is the lower bound and

$u_2 = [-\log(1-\varepsilon)]^{1/\beta}$ is the upper bound.

where $\varepsilon = C/(\beta-1)$ and $C = C_1/C_2$.

B.2 SETHI and CHAND'S Replacement Model:[17]

The problem is stated as follows, A_t denotes a machine of vintage t. The only machine that can be bought at time t is A_t. A new machine can be bought only at the beginning of the period and an existing machine can be sold only at the end of the period.

$Y_t = \{\pi_t, M_{t,k}, S_{t,k}, k >= t\}$

denotes the technology associated with machine A_i where,

π_t = price of A_t at the beginning of period t,

$M_{t,k}$ = neccessary maintenance cost of A_t in period k,

$S_{t,k}$ = the salvage of A_t if sold at the end of period k;

Let n machines be replaced during the length of horizon and let $t_1, t_2, .. t_n = T$ be their salvage times. Then, total cost of this policy is,

$$T = \sum_{i=0}^{n-1} \pi_{t_i+1} + \sum_{i=0}^{n-1} \sum_{k=t_i+1}^{t_{(i+1)}} M_{t_i+1,k} - \sum_{i=0}^{n-1} S_{t_i+1,t(i+1)},$$

where, the first term represents the total purchase price of the n machines used, the second term is the total maintenance cost over the horizon and the last term represents total salvage value of n machines. The finite horizon machine replacement problem then becomes,

$$\underset{n, t_i, i=1,2,..,n-1}{\text{Minimize}} \quad \{\text{Total cost (T)}\}$$

where the minimization requires selection of optimal number of machines and their replacement times.

Definitions:

<u>Purchase Point</u>

A period is defined to be a purchase point (or P-point) if a machine is purchased at the beginning of the period.

<u>Regeneration Point</u>

A period is said to be regeneration point (or R-point) if a machine is salvaged at the end of the period.

A period can be both P-point and R-point if a machine is bought at the beginning of the period and sold at the end of the period. In such a case, the assumption that the P-point precedes the R-point is used.

Any feasible solution satisfies the following purchase-regeneration properties,

1. There is one R-point between any two successive P-points. Moreover, the R-point immediately precedes the second P-point.
2. There is one P-point between any two successive R-points. Moreover, the P-point immediately follows the first R-point.

These properties allow the use an efficient forward algorithm and is described below:

<u>Forward Algorithm (Finite Horizon Case)</u>

Let $C(T)$ denote the minimum cost for the T-period problem (2). Let the notation $< >$ be defined by $\langle n, m\rangle = (n, n + 1, \ldots, m)$. where n and m are nonnegative integers satisfying $m \geq n$. Then,

$$C(T) = \min_{i\, \varepsilon\, \langle O, T-1\rangle} C_j(T)$$

where j is the next to the last R-point with T as the last R-point, and

$$C_j(T) = C(j) + C(j,T)$$

$C(j,T)$ = cost for periods $(j+1)$ to T with $(j+1)$ as the P-point and is given by,

$$C(j,T) = \pi_{j+1} + \sum_{k=j+1}^{T} M_{j+1,k} - S_{j+1,T}$$

and $C(j) = C_j(T-1) - C(j,T-1)$ then $C_j(T)$ can be expressed recursive relationship,

$$C_j(T) = C_j(T-1) - C(j,T-1) + C(j,T)$$

On simplification,

$$C_j(T) = C_j(T-1) + M_{j+1,T} + \Delta S_{j+1,T} \text{ for } j \in \langle \emptyset, T-1\rangle$$

where, $\Delta S_{j+1,T}$ is the amount of decline in the salvage value of

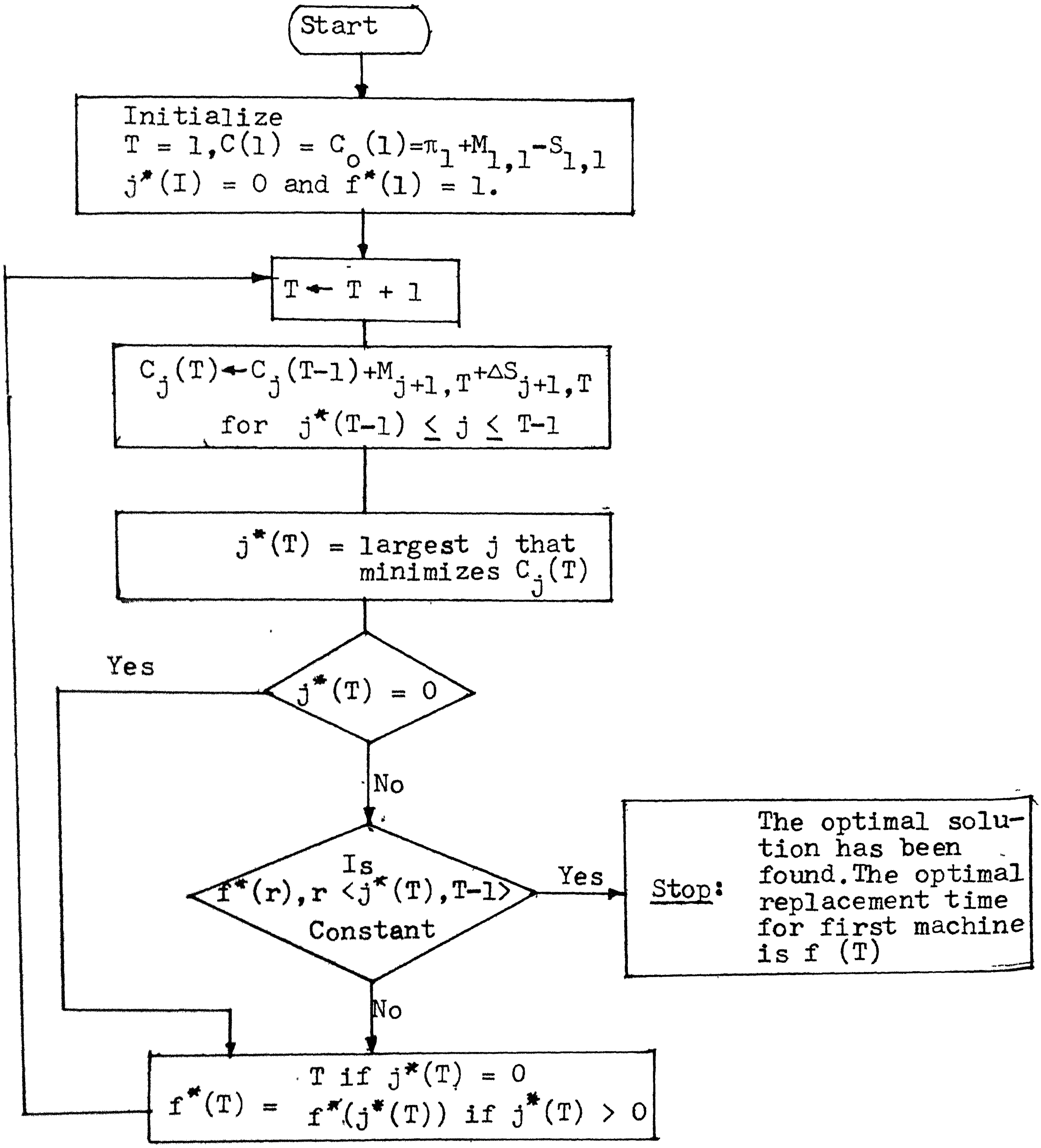


Fig. B.1 Flow chart for the forward algorithm.

machine A_{j+1} during period T.

The operating cost $O_{j,T}$ for machine A_j is,

$M_{j,T} + \Delta S_{j,T}$ for $j \varepsilon \langle 1,T \rangle$

The algorithm is presented in Fig. B.1. Where j(k), denotes the next to last R-point in the optimal solution for the k-period subproblem. The regeneration monotonicity states that j(k) increases with k and f*(r) denotes the period when the first machine is salvaged in an optimal solution to the r-period subproblem. The following theorem is used for finding the end condition:

If f*(r) = H (where H is some constant) for r R(T)- set for some T s.t. j*(T) # Ø, then the salvage time for the first machine is an optimal solution to the infinite horizon problem. H is called the planning horizon and T is called the forecast horizon.

B.3 Replacement Model for a Serially Dependent Multimachine Production System: [16]

The problem is, given a finite horizon T periods where J different machines are used in a serially dependent production system, management must determine during which periods the process must be shut down for replacement. The problem involves balancing of costs. Stinson and Khumawala [16] have formulated this as an integer programming problem and is given below:

$$\text{Min } (\Sigma_{jt\tau} h_{jt\tau} \alpha^{\tau} x_{jt\tau} + \Sigma_{jt} c_{jt} \alpha^{\tau} y_{jt} + \Sigma_{\tau} f_{\tau} z \alpha^{\tau}) \tag{1}$$

$$\text{s.t. } \sum_{0 \leq t \leq \tau} X_{jt} = 1, \; j = 1,\ldots,J; \;\; \tau = 1,\ldots,T \tag{2}$$

$$\emptyset < x_{jt\tau} \leq y_{j\tau}, \quad j = 1,\ldots,J; \; t = 1,\ldots,\tau \; ; \;\; \tau = 1,\ldots,T \tag{3}$$

$$y_{j\tau} < z_{\tau} < 1, \quad j = 1,\ldots,J; \;\; \tau = 1,\ldots,T \tag{4}$$

where all variables x,y,z integer (Ø,1), and

$x_{jt\tau}$ $\begin{cases} = 1 & \text{if machine } j \text{ of vintage } t \text{ is operating in period } \tau \\ = \emptyset & \text{otherwise} \end{cases}$

$y_{j\tau}$ $\begin{cases} = 1 & \text{if machine } j \text{ is replaced at the beginning of period } \tau \\ = \emptyset & \text{otherwise} \end{cases}$

z_τ $\begin{cases} = 1 & \text{if any machine is replaced at the beginning of period } \tau \\ = \emptyset & \text{otherwise} \end{cases}$

$h_{jt\tau}$ = variable cost of operating machine j of vintage in period τ

$c_{j\tau}$ = fixed cost of replacing machine at the beginning of period τ

f = fixed cost of shutting down the entire production system in order to replace one or more machines at the beginning of period τ

α = 1/(1+r) and is used to discount all costs to present value

The objective function seeks to find the values of the integer variable, $x_{jt\tau}$,$y_{j\tau}$ and z_τ which minimizes the total present value operating and fixed costs throughout the planning horizon. Constraint set (2) ensures that a unit of each asset of some vintage is operating in each period. Constraint set (3) ensures that fixed costs are incurred when asset j is renewed in period, and constraint set (4) ensures that the downtime fixed cost f_τ is incurred when one or more assets are replaced in period. The heuristics procedure, as proposed by them is given below.

Step 1: Initialization

Set: Z = {Ø}

Y = {Ø}

T* = T

Z is the set of z_τ values which have been fixed to equal 1

and it defines the periods for which the system is to be down for one or more scheduled replacements. Set Y contains the $y_{j\tau}$ variables fixed at 1 and it defines the machines scheduled to be replaced as well as their replacement periods. T* is defined as the solution horizon and is initially set to T which is the plannning horizon for the problem.

Step 2: Determine the total operating costs over the horizon

Determine the matrix D_j for each of the J machines and the elements of D_j are computed as,

$$d_{jt\tau} = \sum_{\tau^* = \tau} (\alpha^{\tau}) h_{jt\tau^*}$$

The elements represent the total costs of operating machine j of vintage t form period t to the end of the horizon. It represents 'what - if' cost. For example the element d_{113} represents the cost to operate from period 3 to end of the horizon for a vintage 1 machine.

Step 3: Establish a target cost

$$\text{Target } (T^*) = \sum_{j=1}^{J} d_{j\emptyset 1} + \sum_{\tau=1}^{T} f_{\tau} z_{\tau} + \sum_{j=1}^{J} \sum_{\tau=1}^{T} c_{j\tau} y_{j\tau} + \sum_{j=1}^{J} \sum_{t=1}^{T} \sum_{\tau=T+1}^{T} h_{jt\tau} x_{jt\tau}$$

The target cost is the current upper bound on the solution.

Step 4: Ddetermine each machine's cost saving from renewal

For each of the J machines, develop a matrix G_j where each element of G_j is computed as,

$$g_{jt\tau} = d_{jt\tau} - d_{jt^*\tau} - (\alpha^{\tau}) c_{j\tau} \text{ where } t^* = \tau$$

This matrix gives the response for the 'what if' question, i.e. by replacing a machine in the current period, does the savings in the total future operating costs offset the fixed cost of replacement?.

Step 5: Determine system cost savings resulting form renewal

Combine all G_j matrices into a matrix E where each element of E is computed as,

$$e_{t\tau} = \sum_{j=1}^{J} \max(o, g_{jt\tau}) - (\alpha^{\tau}) f_{\tau}$$

This matrix gives the possible heuristics solutions.

Step 6: Roll back later period cost savings into earlier periods:

In this step the objective is to 'roll-back' the cost savings of replacements in later periods into earlier periods. This is for identifying the better heuristic solutions for problems where the planning horizon is long. The matrix with rolled back savings is denoted as M, and initially it is equal to E. Identify the bottom-most row of M which contains a non-negative element; this row is labelled as I. The largest non-negative element is then added to all non-negative elements in column I. m't as an updated element of M,

$$m'_{t} = \begin{cases} m_{tI} + \max\limits_{\text{all } \tau}(o, m_{i}) \text{ if } m_{tI\tau} > 0 \\ = m_{tI} \quad \text{otherwise} \end{cases}$$

The calculation of this step are repeated for row I-1 etc., until I = 1.

Step 7: Augment the solution

If $\max\limits_{\text{all } \tau}(m_{o\tau}) < \emptyset$

terminate the procedure; the heuristic solution is the current membership of sets Z and Y. Otherwise, the solution identified by,

$$\max_{\text{all } \tau}(m_{o\tau})$$

and denote L as the last replacement period of the solution.

Augment $Z = Z \cup \{ z_L \}$

Augment $Y = Y \cup \{ y_{j\tau} \} / g_{jt^*\tau^*} > \emptyset$; where $t^* = L$; and $\tau^* = L$

Set $T^* = L - 1$ and return to Step 2

Steps 1-6 are repeated until there is no cost improvement.

B.4 Terborgh's Replacement Model :[25]

The deterioration cost for the machine and the obsolescence rate given by [25] are,

$$D_m = D_{m-1} + \beta, \quad C_m = C_{m-1} + \alpha .$$

where,

D_m is the cost of deterioration in period m with $D_o = \gamma'$,

and C_m is the cost of obsolscence in period m, with $C_o = \emptyset$.

The operating cost for any period is given as,

$$\gamma' + \beta_m - \alpha kL,$$

where k corresponds to the kth replacement in the chain. The present worth of cost based on replacing every L period is,

$$PW(L) = \sum_{k=0}^{\infty} (1+r)^{-kL} \left\{ \sum_{m=1}^{L} [(\gamma' - \alpha kL + \beta m)(1 + r)^{-m}] + W - S_L(1 + r)^{-L} \right\}$$

where,

r is the time value of money,

W is the initial purchase price,

S_L is the salvage value at period L

The After-Tax present worth as derived by Leung [25] is,

$$PW(L) = \sum_{k=0}^{\infty} (1+r)^{-kL} \left\{ (1+r)^{-1} \sum_{n=0}^{L-1} [(1-\rho)(\gamma - akL + \beta n) \times (1+r)^{-n}] + WM \right\}$$

where,

$$M = \begin{cases} 1-\sum_{n=1}^{L} \rho\, T_n(1+r)^{-n} - [1-\sum_{n=1}^{L} T_n](1+r)^{-L} + T_L\rho(1+r)^{-L}, & L \leq h \\ 1 - \sum_{n=1}^{h} \rho\, T_n(1+r)^{-n}, & L > h, \end{cases}$$

T is the corresponding depreciation percentage at year n,

h is the depreciable life.

Using the Z-transform the above equation is translated as,

$$PW(L) = Z\{f(kL)\} = \sum_{k=0}^{\infty} f(kL)[(1+r)^{L}]^{-k},$$

where f(kL) is expressed as,

$$f(kL) = \frac{1-\rho}{r(1+r)^{L}} \{[(1+r)^{L}-1]\ (\gamma-\alpha kL + \frac{\beta}{r}) - \beta L\} + WM$$

When discount and tax rate are known, the value of M varies with replacement period L when replacement occurs within the depreciable life (h) and can be found out by enumeration. When replacement occurs beyond the depreciable life (h), then M is constant and the determination of L solely involves the minimzation of the expression,

$$f(L) = \frac{rWM - (\alpha+\beta)(1-\rho)L}{(1+r)^{L} - 1}$$

The f(L) curve will start out at positive infinity decrease monotonoically towards a certain negative value and then converges asymptotically to zero from the negative side. Thus, a global minimum for replacement period(L*) exists.

B.5 Mong's Replacement Model : [34]

The problem of block replacement policy is formulated as:

A unit is made up of n components and the life distribution is the order statistic Z,

$$Z = \min\{x_1, x_2, \ldots\ldots, x_n\}$$

where,

X_i's are the life of individual components and the component's life distribution follows the Normal distribution. The condition to be satisfied for block replacement policy is,

$$C/\mu_z < \sum_{i=1}^{n} C_i/\mu_i$$

where,

μ_z = mean life of the unit,

C_i = cost of replacing only component i,

C = cost of replacing the entire unit.

Calculation of :

The p.d.f of Z can be obtained by considering the consitional p.d.f of Z, $g(Z/\ Z = X_i)$, when component i fails first:

$$g(Z/Z = X_i) = f_i(Z) \times \Pr(X_j > Z \text{ for alll } j,\ j \neq i)$$
$$= f_i(Z) \prod_{\substack{j=1 \\ j\neq i}}^{n} \int_{Z}^{\infty} f_j(t)dt$$

Since the failure of the first component mutually excludes the other components from failing first, the above equation can be summed over i to obtain the p.d.f of Z:

$$g(Z) = \sum_{i=1}^{n} f_i(Z) \times \prod_{\substack{j=1 \\ j\neq i}}^{n} \int_{Z}^{\infty} f_i(t)dt$$

thus, the mean of Z is given by :

$$z = \int_{-\infty}^{\infty} x\ g(x)dx$$

B.6 Flow-through Method

This method for calculating minimum annual revenue requirements allocates credits and costs in the year they occur; Also the capitalized interest is taken as an expense in the first year. The various steps involved are,

Step 1: determine the capatilized interest. (gP)

Step 2: calculate the depreciation schedule.

Step 3: calculate investment tax credit rate.

Step 4: determine the yearly costs. These costs include maintenance and operation costs.

Step 5: calculate the chargeable investment, K_x,

$K_x = K_{x-1} + D_{bx}$ where D_{bx} is the depreciation for book puropse.

Step 6: calculate the debt interest. I_x

Step 7: calculate the required return on equity as,

$f_{ex} = k_e(1-c)K_{x-1}$

where k_e is the required rate of return on equity and c is debt ratio.

Step 8: calculate the taxes: t_x

Step 9: calculate the minimum annual revenue requirements R_x,

$$R_x = D_{bx} + f_{ex} + I_x + gP + C_x + t_x$$

APPENDIX - C

STRUCTURE OF DATABASE FILES

Structure for database: C:mcdata.dbf
Number of data records: 12
Date of last update : 02/08/88

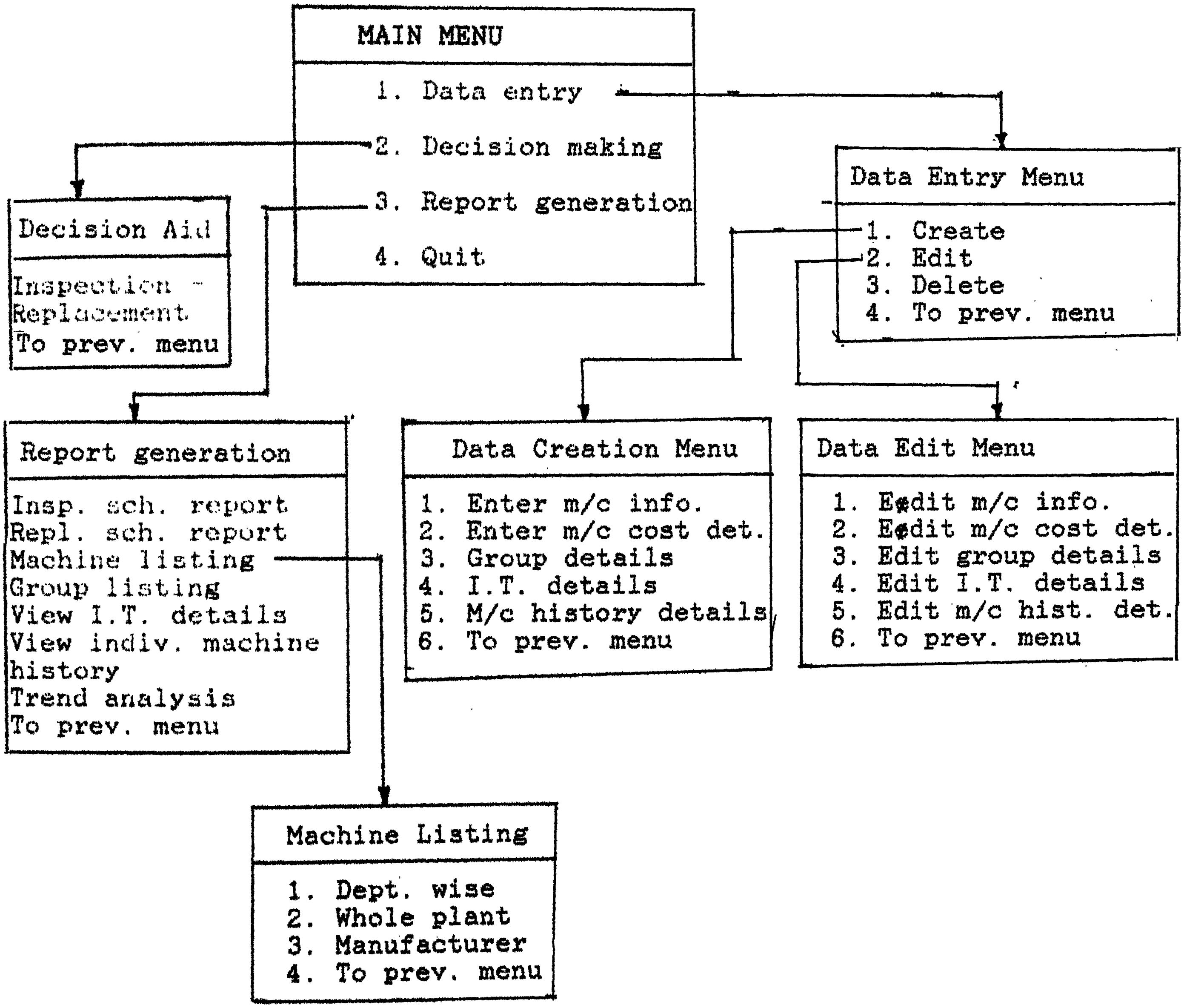
Field	Field Name	Type	Width	Dec
1	MCCODE	Numeric	6	
2	NAME	Character	15	
3	DEPT	Character	10	
4	INST_DATE	Date	8	
5	PRIOR_CODE	Numeric	2	
6	SINGLE_MUL	Character	1	
7	MULTI_S_D	Character	1	
8	EST_LIFE	Numeric	2	
9	EST_SALV	Numeric	10	2
10	MANUFACTER	Character	15	
11	MODEL_TYPE	Character	10	
12	MFR_CONTAC	Character	15	
13	PHONE	Numeric	6	
14	GROUP_CODE	Numeric	2	
15	INSP_FREQ	Numeric	3	
16	NEXT_INSP	Date	8	
17	INSP_AFFE	Character	1	
18	SUBSYS_NO	Numeric	2	
19	INSP_START	Date	8	
20	REP_DATE	Date	8	
21	PURC_COST	Numeric	10	2
22	REP_COST	Numeric	10	2
23	INSP_COST	Numeric	10	2
24	DOWN_COST	Numeric	10	2
25	BONUS_COST	Numeric	10	2
26	SETUP_COST	Numeric	10	2
** Total **			194	

Structure for database: C:mchistor.dbf
Number of data records: 13
Date of last update : 02/03/88

Field	Field Name	Type	Width	Dec
1	MCCODE	Numeric	10	
2	WORK_TYPE	Character	4	
3	TIME_TAKEN	Numeric	6	2
4	LABOUR_COS	Numeric	10	2
5	MATERIAL_C	Numeric	10	2
6	WHICH_DATE	Date	8	
7	SETUP_TIME	Numeric	6	2
8	OPR_TIME	Numeric	8	2
** Total **			63	

APPENDIX - D

MENU STRUCTURE



APPENDIX E

INSPECTION SCHEDULE FOR THE WEEK

MACHINE CODE	NAME	INSP. DATE	INSP. FREQ (in days)
** For the equipments in GEAR DIV			
* PRIORITY 1			
12345	HORI_DRILL	12/02/88	200.00
11111	MILLING MC	14/02/88	60.00
* PRIORITY 3			
45	UNIV DRILL	13/02/88	500.00
204060	HORZ_MILL	14/02/88	60.00
346565	PLANNER	12/02/88	42.00
* PRIORITY 4			
131133	VERT-MILL	15/02/88	20.00

MACHINES TO BE REPLACED IN THE YEAR

MACHINE CODE	NAME	INSTALLATION DATE	PURCHASE PRICE	ESTINATED SALV. VALUE	ESTIMATED LIFE	APPROX. REP -LACEMENT DAT
** IN THE DEPT OF GEAR DIV						
* PRIORITY 1						
12345	HORI_DRILL	01/11/85	200000.00	25000.00	10.0	09/01/93
11111	MILLING MC	08/01/87	110000.00	31000.00	9.0	02/02/93
* PRIORITY 3						
45	UNIV DRILL	03/15/84	346767.00	65000.00	12.0	04/03/93
* PRIORITY 4						
131133	VERT-MILL	03/21/80	350000.00	45000.00	16.0	23/09/93
* PRIORITY 5						
204060	HORZ_MILL	01/01/78	900000.00	15000.00	20.0	11/11/93
346565	PLANNER	02/20/86	80000.00	20000.00	9.0	09/09/93